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THE INFLUENCE OF SOIL SUCTION ON THE SHEAR STRENGTH OF UNSATURATED SOIL

by

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A laboratory investigation was conducted to assess the influence of suction on the shear strength of unsaturated soil. Variables which were investigated included the effects of compacting specimens of an expansive clay at different water contents, shearing specimens at various densities, and adding potassium chloride ~~(KCl)~~ (KCl) to the pore fluid of selected specimens.

To assess the influence of matrix suction on the shear strength of unsaturated soil, specimens were compacted at water contents wet or dry of optimum and consolidated by selected stresses to various densities prior to shear. The effects of density on the strengths of both saturated and unsaturated specimens were normalized by Hvorslev's "true friction-true cohesion" concept. Constant water content tests were conducted on all unsaturated specimens, although drainage of pore water may

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Clay soils	Expansive soils	Soil mechanics
Compaction tests	Partially saturated soils	Soil suction
Consolidation tests	Psychrometer	Strength tests
		Unsaturated soils

19. ABSTRACT (Continued).

have occurred as some specimens are consolidated to high degrees of saturation by the applied stresses.

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It was determined that shear strengths of unsaturated soils were dependent on the applied stress, density, and water content of specimens at failure. A modified Mohr-Coulomb strength relationship was proposed to predict the shear strength of unsaturated soils. The effect of matrix suction was to increase the value of the cohesion intercept in this model, although the measurement of suction was not required to apply the model.

A method was proposed to characterize the influence of matrix suction on the shear strengths of unsaturated soils. It was determined that the magnitude of suction depended on ~~was dependent upon the~~ water content and the degree of saturation of the saturated specimens at failure while the effect of suction was a variable which was dependent upon the degree of saturation of the specimens.

To assess the influence of solute suction on the shear strengths of unsaturated soil, selected specimens were treated with ~~KCl~~ KCL prior to compaction. The effect of solute suction was to increase the value of the cohesion in the modified Mohr-Coulomb strength relationship. As compared to untreated specimens, the effects of matrix suction in treated specimens were reduced.

Keywords: Soil mechanics; Saturated soils; Soil stabilization; Soils/compacting/expansion; Shear strength; Pore pressure; Clay/montmorillonite; Potassium chloride; Soil tests; Moisture content; Cohesive soils. (MM)

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PREFACE

This manuscript was submitted to the Office of Graduate Studies of Texas A&M University in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering. Partial funding for the study was provided by the RDT&E Work Unit AT22/AO/006, "Characterization of Shear Strength by Soil Suction in Swelling Soils." The report was published using funds provided by CWR&D Work Unit 31173, "Special Studies." Messrs. A. F. Muller (retired) and Richard F. Davidson, US Army Corps of Engineers, were the Technical Monitors for these programs.

The work reported herein was performed by Dr. Richard W. Peterson, Soils Research Center (SRC), Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES). The advice and encouragement offered by Drs. Victor H. Torrey, III and Lawrence D. Johnson and Mr. Robert T. Donaghe, S&RMD, is gratefully acknowledged. The assistance of the employees of S&RMD is appreciated. General supervision was provided by Mr. G. P. Hale, Chief, SRC; Dr. Don C. Banks, Chief, S&RMD; and Dr. William F. Marcuson III, Chief, GL.

COL Larry B. Fulton, EN, was Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
foot-pounds per cubic foot	0.048	kiloJoules per cubic metre
inches	2.54	centimetres
pounds (force) per square inch	6.894757	kilopascals
pounds (mass) per cubic foot	16.0846	kilograms per cubic metre
tons (force) per square foot	95.76052	kilopascals
tons (mass) per square foot	9,764.856	kilograms per square metre

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

THE INFLUENCE OF SOIL SUCTION ON THE SHEAR STRENGTH OF UNSATURATED SOIL

INTRODUCTION

Background

Years of experience coupled with an understanding of the effective stress theory for saturated soils have allowed the profession to design embankments and foundations of saturated soils with confidence. This is not the case for the performance of structures and foundations of unsaturated soils. Numerous failures of compacted embankments, excavated and natural slopes, and foundations of unsaturated soils have been documented. Stability problems have been reported as slough slides along the Mississippi River mainline levees (U.S. Army Corps of Engineers, Vicksburg District, 1983), slope and roadway embankment failures in Nigeria (Adegoke-Anthony and Agada, 1982), and natural and excavated slope failures in Hong Kong (Boonsinsuk and Yong, 1982). Foundation problems caused by expansive soils (Jones and Holtz, 1973) and collapsible soils (Hale, 1982) have also been documented. However, few investigations of unsaturated soil behavior have been conducted.

The lack of an appropriate theory for unsaturated soil behavior is a result of several factors. First, the failures of embankments and foundations of unsaturated soils generally have not been catastrophic in terms of life and property damage, as compared to the breach of a dam. Therefore, monies to study the engineering behavior of unsaturated soils have generally not been available because the cost of the research often was perceived to outweigh the benefits. Consequently, the stress conditions and mechanisms involved as well as the soil properties which must be measured have not been fully understood. As a result, appropriate theoretical models to predict the behavior of unsaturated soil do not exist. Accordingly, the design of embankments and foundations of unsaturated soils has remained largely empirical and overly expensive either because of extremely conservative design assumptions which result in excessive construction costs or in terms of

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less conservative design assumptions which result in excessive maintenance and repair costs during the life of the structure.

As a result of an article by Jones and Holtz (1973) which documented the monetary damage caused by expansive soils, extensive research was initiated and significant advances regarding theories of the behavior of expansive soils have resulted. Unfortunately, few investigations of the behavior of unsaturated soils have been reported. However, drawing an analogy that under certain conditions the engineering behavior of unsaturated soils is similar to the engineering behavior of expansive soils, i.e. both soils would tend to imbibe or expel water which could result in a change of volume, a change of shear strength, or both, significant technological advances with respect to a theory for unsaturated soils may have also resulted.

Under the auspices of the Research, Development, Technology and Evaluation (RDT&E) Program, a laboratory investigation of the behavior of unsaturated soils was conducted. Specifically, the investigation was formulated to assess the influence of soil suction on the shear strength of an expansive clay soil. The RDT&E work unit, "Characterization of Shear Strength by Soil Suction in Swelling Cohesive Soils," provided partial funding for the research.

Objective

The objective of this research was to assess the influence of soil suction on the shear strength of unsaturated soil.

Scope

Before a meaningful investigation could be conducted, a working knowledge of the behavior of unsaturated and expansive soils as well as an understanding of terms commonly associated with expansive soils, such as soil suction, were a necessity. A comprehensive literature survey was conducted to identify methods of characterizing shear strengths of soil by suction and to minimize the potential of repeating the shortcomings of previous investigations or developing a theory or

model which could not be used for practical applications. Lastly, laboratory equipment and test procedures were designed or modified as required to ensure that a quality investigation could be conducted.

The scope of the investigation was conveniently divided into four phases. Phase I, which consisted of perusing the literature and evaluating models which incorporated soil suction for the assessment of the shear strengths of unsaturated soils, is reported in the section entitled "Literature Review". Phase II included the formulation of a research plan to assess the influence of suction on the shear strength of unsaturated soil and the development and evaluation of laboratory equipment, methods and procedures to execute the investigation. These studies are reported in the sections entitled "Research Plan" and "Materials and Test Methodology", respectively. Following the successful implementation of Phases I and II, a laboratory investigation was conducted and the data were analyzed. Results are reported in the section entitled "Test Results and Analysis of Data". Phase IV consisted of the selection and evaluation of a shear strength model for unsaturated soils and is reported in the section entitled "Model and Performance". Conclusions obtained during the investigation and suggestions for additional research on the shear strength of unsaturated soils are discussed in the section entitled "Conclusions and Recommendations". References cited in the study follow. Laboratory test results, including x-ray diffraction and electrical conductivity tests, compaction tests, suction tests, consolidation tests and triaxial compression tests on saturated specimens, unsaturated specimens and unsaturated specimens treated with potassium chloride (KCl) are presented in Appendices I through VII, respectively.

REVIEW OF PREVIOUS RESEARCH

Mechanisms which Influence the Behavior of Clay Soil

Three natural microscale mechanisms which influence much of the behavior of cohesive soils include clay particle attraction, cation hydration and osmotic repulsion (Snethen, Johnson and Patrick, 1977). Two other mechanisms which influence soil behavior are elastic bending of the clay particles and capillarity from surface tension in the pore fluid (Snethen, Johnson and Patrick, 1977).

Clay particle attraction is the surface attraction between clay mineral particles, between the clay mineral and water, and between the clay mineral and cations in the pore water which occur as a result of the shape and internal crystalline structure of the clay mineral. The clay mineral consists of tiny, relatively thin platelets with faces and edges. The faces of the platelets tend to be flat, contain most of the platelet surface area, and possess a net negative charge, as in the case of montmorillonites and illites. The edges are generally irregularly shaped and may be either positively or negatively charged depending on the number and type of broken bonds at the edge surface.

The substitution of cations of lower valence in the tetrahedral and octahedral layers of the molecular sheets is the source of the net negative charges in the particles. For example, the divalent magnesium cation is commonly substituted for the trivalent aluminum cation in the octahedral layer of montmorillonites. The negative charge in the mineral platelets leads to the adsorption of positively charged "exchangeable" cations such as sodium and calcium on the particle surfaces. Although the negative charge may be rendered neutral in a charge deficiency sense, a considerable force for the attraction of water in the form of hydration of the cations may exist.

Water molecules are attracted and held to the particle surfaces through the hydrogen bonding of the water molecule to the clay mineral surface using dipole to dipole attraction of the water molecule. The exposed oxygens of the platelets attract and bond with the positive side of dipolar water molecules while hydroxyls attract and bond with

the negative side of dipolar water molecules. Such hydrogen bonding provides the basic building blocks for the layered or oriented (double layer) water on the clay particles and is an important source of the force per unit area or suction which may influence soil shear strength.

The mechanism of osmotic repulsion occurs when the platelet-water-cation system of the soil comes into contact with an external pore fluid of different ionic concentration. The double layer system acts like a semipermeable membrane which allows water molecules to enter or to leave such that the ionic concentrations of the double layer system and the external pore fluid become balanced. An attraction for water into the platelet-water-cation system occurs when the external pore fluid contains less cations than within the system. Water is expelled from the system if the concentration of salts is greater in the external pore fluid than within the system. The efficiency in which external water is moved into a soil depends upon the concentration and type of dissolved salts in the pore water (Kemper and Rollins, 1966).

Clay mineral platelets can be held in bent positions by either external loading stresses or through internal soil suction pressures which force particles closer together. Elastic bending of clay mineral platelets is presumably introduced during consolidation, compression or desiccation of a soil mass. Following release of the pressure, much of the elastic bending strain energy may remain in the platelets. Mitchell and McConnell (1965) reported a study of the elastic strain energy stored in a kaolinite clay; values of recoverable elastic strain as a function of stress intensity were higher for specimens with flocculated structures as compared to specimens with dispersed structures.

Surface tension forces occur from broken molecular bonds of the air-liquid interface in partially saturated soils, hereinafter referred to as unsaturated soils. As a result of these forces, the surface liquid molecules tend to draw together. By considering the statics of a cylindrical capillary column of diameter, d, above a free water surface, surface tension forces can be illustrated as in Figure 1:

$$\text{Force of the surface tension} = (\pi \ d \ T_s) \cos \alpha \qquad (1)$$

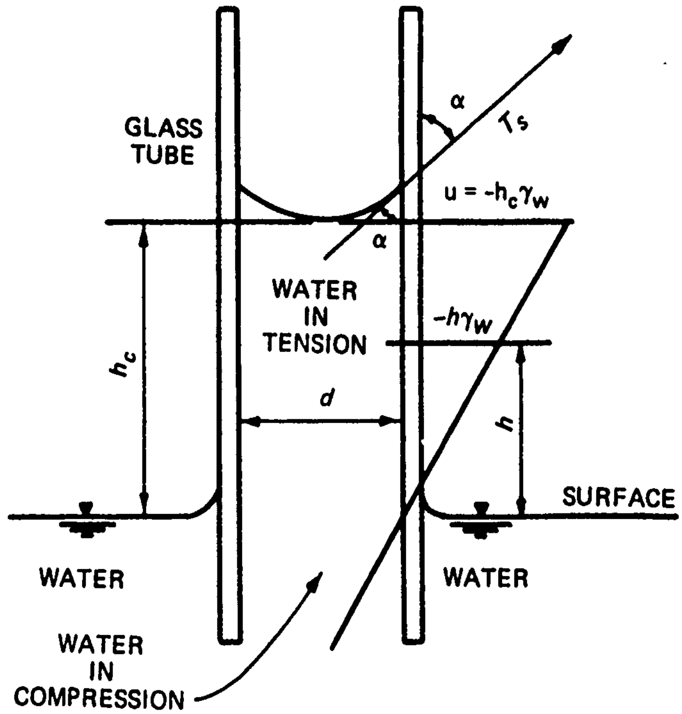


FIG. 1. Schematic representation of a capillary tube in water.

where

T_s = surface tension

α = the angle which water intersects the wall of the capillary tube; $\alpha = 0$ for clean glass

and

$$\text{Weight of water in the tube} = (\pi\ d^2\ h_c\ \gamma_w)/4 \tag{2}$$

where

h_c = height of capillary rise

γ_w = unit weight of water

Equating Equations 1 and 2 and rearranging the terms:

$$h_c = [(4\ T_s\ \gamma_w)/d]\ \cos\alpha \tag{3}$$

Equation 3 indicates that as the diameter of the meniscus decreases, capillary stress increases. By analogy, capillary stresses increase as drying of clay soil occurs.

Soil Suction

Unsaturated soils, especially montmorillonitic clays, possess an affinity for water that can lead to alterations of the engineering behavior of the soil. Imbibing water often leads to changes of shear strength and differential heave or collapse of the soil mass. A measure of the affinity for soil to retain water, i.e. the water content, can be expressed quantitatively by the magnitude of the negative pore water pressure or suction (Croney and Coleman, 1961; Johnson, 1974a, 1974b; Olson and Langfelder, 1965; Snethen and Johnson, 1980; Snethen, Johnson and Patrick, 1977). The apparent significance of negative pore water pressures in soils has stimulated many programs to develop techniques to measure suction and to evaluate its influence on soil behavior.

Suction is a measure of the driving force which causes moisture to flow. It is defined as the relative capability of pore water to do

work as compared to a pool or reservoir of pure water at the same temperature. The Statement of the Review Panel (1965) defined this "free energy" as "the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water." Table 1 summarizes the Statement of the Review Panel (1965).

Although total suction is the formal term, "suction" is preferred. It is frequently expressed in terms of pF (Croney and Coleman, 1961; Dumbleton and West, 1970):

$$pF = \mathrm{Log}_{10}\ (h_w/h) \tag{4}$$

where

pF = logarithmic value of the free energy or suction

h_w = head of water, cm

h = 1 cm

Concepts of suction are based upon energy principles from thermodynamics. Total suction may be conveniently determined by measuring the relative humidity within a mass of soil by a thermocouple psychrometer. Suction can be expressed quantitatively (Rawlins and Dalton, 1967; Richards, 1969; Statement of the Review Panel, 1965) as:

$$h_t = -(RT/v_w)\ \log_e\ (p/p_o) \tag{5}$$

where

h_t = total suction, tsf (1 tsf = 96 kPa)

R = ideal gas constant (86.82 cc-tsf/deg K-mole)

T = absolute temperature, deg K

v_w = volume of a mole of liquid water (18.02 cc/mole)

p = pressure of water vapor, tsf

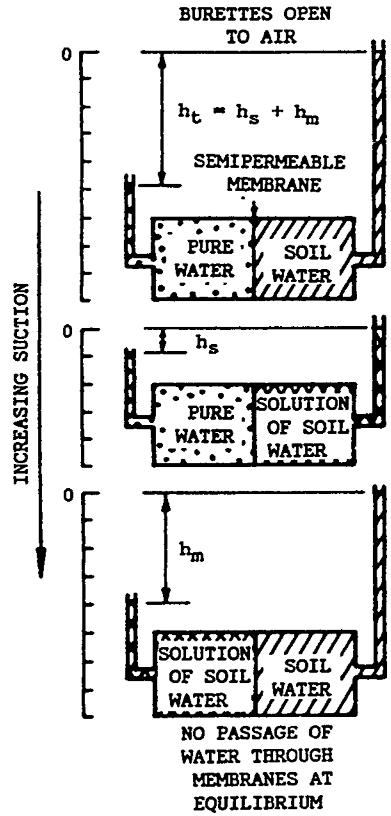
p_o = pressure of saturated water vapor, tsf

p/p_o = relative humidity

Table 1. Definitions of Suction
(After Statement of the Review Panel, 1965)

Term	Symbol	Definition
Total suction	h_t	The negative gage pressure, relative to the external gas pressure* on the soil water, to which a pool of pure water must be subjected in order to be in equilibrium through a semi-permeable (permeable to water molecules only) membrane with the soil water.
Osmotic (solute) suction	h_s	The negative gage pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable membrane with a pool containing a solution identical in composition with the soil water.
Matrix (soil water) suction	h_m	The negative gage pressure, relative to the external gas pressure* on the soil water, to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with the soil water.

Illustration



* The magnitude of matrix suction is reduced by the magnitude of the external gas pressure. Osmotic suction is determined by the concentration of soluble salts in the pore water and can be given by Equation 5.

Total suction is the algebraic sum of the matrix suction* and osmotic suction components (Statement of the Review Panel, 1965), as given by Equation 6:

$$h_t = h_s + h_m \qquad (6)$$

where

h_s = osmotic or solute suction

h_m = matrix suction

Osmotic suction is the result of the lowering of the relative humidity of the pore fluid by the presence or concentration of soluble salts in the pore water. Matrix suction is the negative pore water pressure or capillary stress in soils and can be related to pore air and pore water pressures by Equation 7 (Blight, 1965; Barden, Madedor and Sides, 1969; Fredlund, 1979; Hilf, 1956; Matyas and Radhakrishna, 1968; U.S. Department of the Interior Bureau of Reclamation, 1966):

$$h_m = u_a - u_w \qquad (7)$$

where

u_a = pore air pressure

u_w = pore water pressure

Pore air pressure is usually taken as zero for atmospheric pressure. As the soil becomes saturated, pore air pressure becomes equal to the pore water pressure.

A direct measurement of matrix suction can be accomplished by using a high air entry (high bubbling pressure) membrane or pressure plate apparatus (U.S. Department of the Interior Bureau of Reclamation, 1966). The simplest configuration consists of a pressure plate or membrane which separates the soil specimen from a container of water, as presented conceptually in Figure 2. As the capillary stresses within the soil specimen cause water to flow through the pressure plate, the

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* The Statement of the Review Panel (1965) identified the term as "matrix suction". Although matric suction is grammatically correct (Parker, 1984), the term matrix suction was used throughout the text.

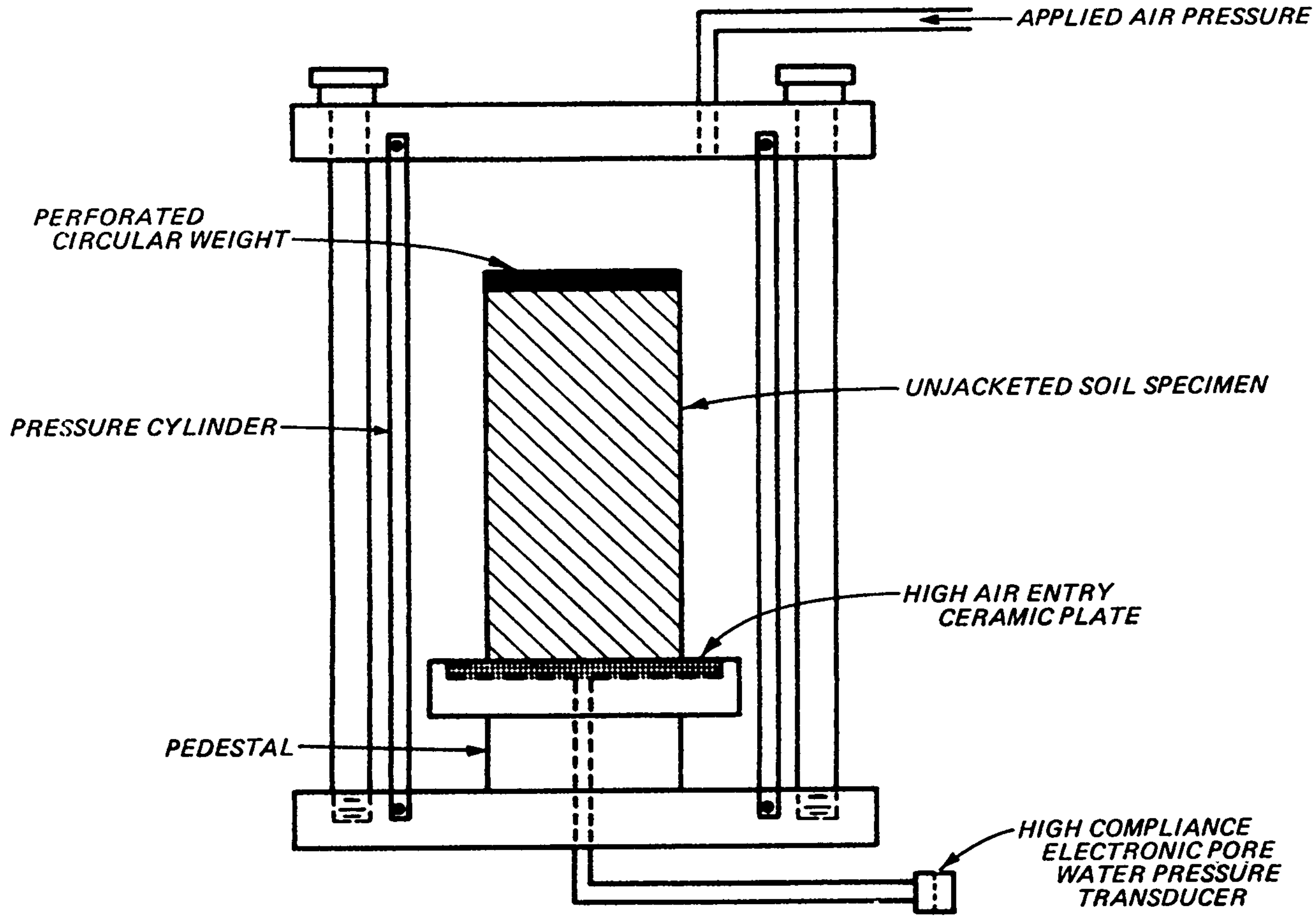

FIG.2. Schematic representation of an exposed end plate test for determining matrix suction (After U.S. Department of the Interior Bureau of Reclamation, 1974).

absolute water pressure in the container of water is reduced to less than one atmosphere. To prevent cavitation of the water in the container, air pressure is simultaneously applied to the soil specimen and pressure plate. This process is incrementally repeated until the capillary stresses are in equilibrium with the test environment, i.e. the water does not flow. The algebraic difference between the pore air pressure and the pore water pressure is matrix suction. By the axis translation technique, which is illustrated in Figure 3, the value of capillary stress or matrix suction can be determined.

An indirect measurement of matrix suction within a soil mass can be made with a thermocouple psychrometer. The principle consists of measuring the relative humidity of air in the voids of the soil specimen; measurements are converted to total suction by Equation 5. However, the value of osmotic suction must be obtained from an independent measurement of the relative humidity of an extract of the pore fluid and subtracted from the value of total suction, as shown by Equation 6.

Influence of Matrix Suction on Shear Strength

Hilf (1956) conducted one of the first investigations of negative pore water pressures in compacted cohesive soils. He proposed a Mohr-Coulomb strength relationship of the form of Equation 8 to describe the shear strengths of unsaturated soils:

$$\tau = c + \sigma' \tan \phi \tag{8}$$

where

τ = shear strength

c = cohesion

ϕ = internal friction

and

$$\sigma' = (\sigma - u_a) - u_c \tag{9}$$

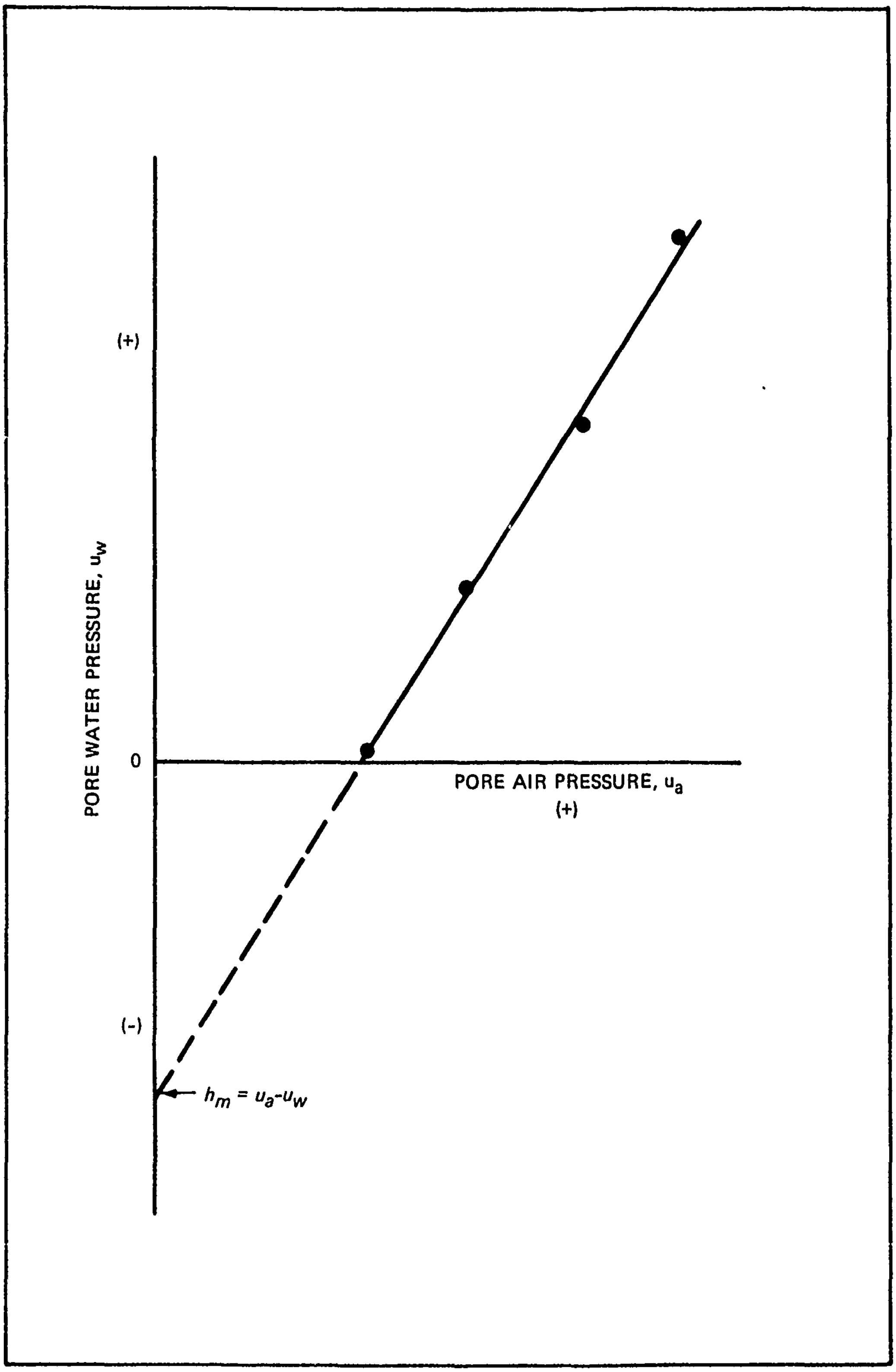

FIG. 3. Determination of matrix suction using the axis translation technique.

where

σ' = effective normal stress

σ = external normal stress

u_c = capillary stress = - $(u_a - u_w)$

Guided by the success of the effective stress equation for saturated soils, Bishop, Alpan, Blight and Donald (1961) suggested a modified effective stress relationship for unsaturated soils:

$$\sigma' = (\sigma - u_a) + \chi\ (u_a - u_w) \tag{10}$$

where

σ' = effective stress

σ = total normal stress

u_a = pore air pressure

u_w = pore water pressure

χ = a pore pressure parameter which varied from 0 to 1 as saturation varied from 0 to 100 percent

Unsaturated shear strengths were expressed in the form of a modified Mohr-Coulomb strength relationship (Bishop, Alpan, Blight and Donald, 1961) as:

$$\tau = c' + [(\sigma - u_a) + \chi(u_a - u_w)] \tan \phi' \tag{11}$$

where

τ = shear strength

c' = apparent cohesion in terms of effective stress

ϕ' = angle of shearing resistance in terms of effective stress

Blight (1967) fundamentally explained the behavior of the χ factor when influenced by surface tension as:

$$\chi = [(\pi\ A)/2]\ [A/2 - T_s/(r\ h_m)] \tag{12}$$

where

$A = \tan\theta - \sec\theta + 1$

θ = an angle, measured with respect to the radius of a spherical particle, which is formed between the contact of two spheres and the location where the meniscus is tangent to the surface of one of the spheres

r = radius of the spherical particle

T_s = surface tension of the liquid

h_m = pore pressure, $(u_a - u_w)$

Blight determined the pressure h_m as:

$$h_m = - [T_s/r\ A]\ [2 - \sin\theta/(1 - \cos\theta)] \tag{13}$$

Substituting Equation 13 into Equation 12 and rearranging the terms yields:

$$\chi = [(\pi\ A^2)/4]\ [\sin\theta/(\sin\theta + 2\cos\theta - 2)] \tag{14}$$

Equation 12 shows that χ is dependent upon the surface tension of the pore water and the suction pressures. For conditions of identical surface tensions, the magnitude of χ will vary inversely to the suction pressure. Equation 14 shows that χ is a function of the angle θ. The maximum value of χ is 1.57 for θ equal to 45 degrees; larger values of θ are not possible because air becomes occluded.

In practice, the χ factor for unsaturated soils did not work well. Blight (1967) reported two methods for evaluating χ; each method yielded different results. He was unable to decide which method was correct. Fredlund, Morgenstern and Widger (1978) reported that a decrease in pore water pressure increased the frictional resistance of a mixture of 80 percent potters flint and 20 percent peerless clay more than the corresponding increase in confining pressure. This observation implied that χ was greater than one. Gulhati and Satija (1981) presented test results which demonstrated that χ was greater than one for unsaturated specimens. Jennings and Burland (1962) demonstrated that χ could have negative values for collapsible soils.

In 1979, Fredlund (1979) proposed a theory for unsaturated soils. He postulated that unsaturated soil was a four phase system consisting of solids, water, a continuous air phase and contractile skin (or air-water interface). Based upon an analysis consistent with multiphase continuum mechanics, he proposed two independent stress tensors. Conceptually, Fredlund suggested the shear strength of an unsaturated soil could be expressed in the form of an extended, or three dimensional, Mohr-Coulomb strength relationship as:

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \qquad (15)$$

where

τ = shear strength

c' = cohesion intercept when the two stress variables are zero

$(\sigma - u_a)$ = stress variable, applied stress

$(u_a - u_w)$ = stress variable, matrix suction

ϕ' = angle of friction with respect to applied stress

ϕ^b = angle of friction with respect to matrix suction

which is illustrated in Figure 4. Furthermore, he suggested there was a smooth transition from the unsaturated to the saturated case. As the degree of saturation approached 100 percent, the pore air pressure and pore water pressure would become equal, matrix suction, $(u_a - u_w)$, would go to zero and pore water pressure could be substituted for pore air pressure in the applied stress variable, $(\sigma - u_a)$. The c' and ϕ' strength parameters could be evaluated in the conventional manner for saturated soils.

Ho and Fredlund (1982a) and Chantawarangul (1983) reanalyzed test results for several soils reported in the literature using the unsaturated shear strength model given as Equation 15. Values for the angle of friction, ϕ^b, ranged from 4 to 35 degrees; ϕ^b was frequently one-third to two-thirds of the angle of friction, ϕ'. Typical values of ϕ^b obtained from specimens of boulder clay, compacted shale and Dhanauri clay are summarized in Table 2.

Based upon the results of linear regression analyses for evaluating ϕ^b, the extended Mohr-Coulomb relationship for predicting the shear

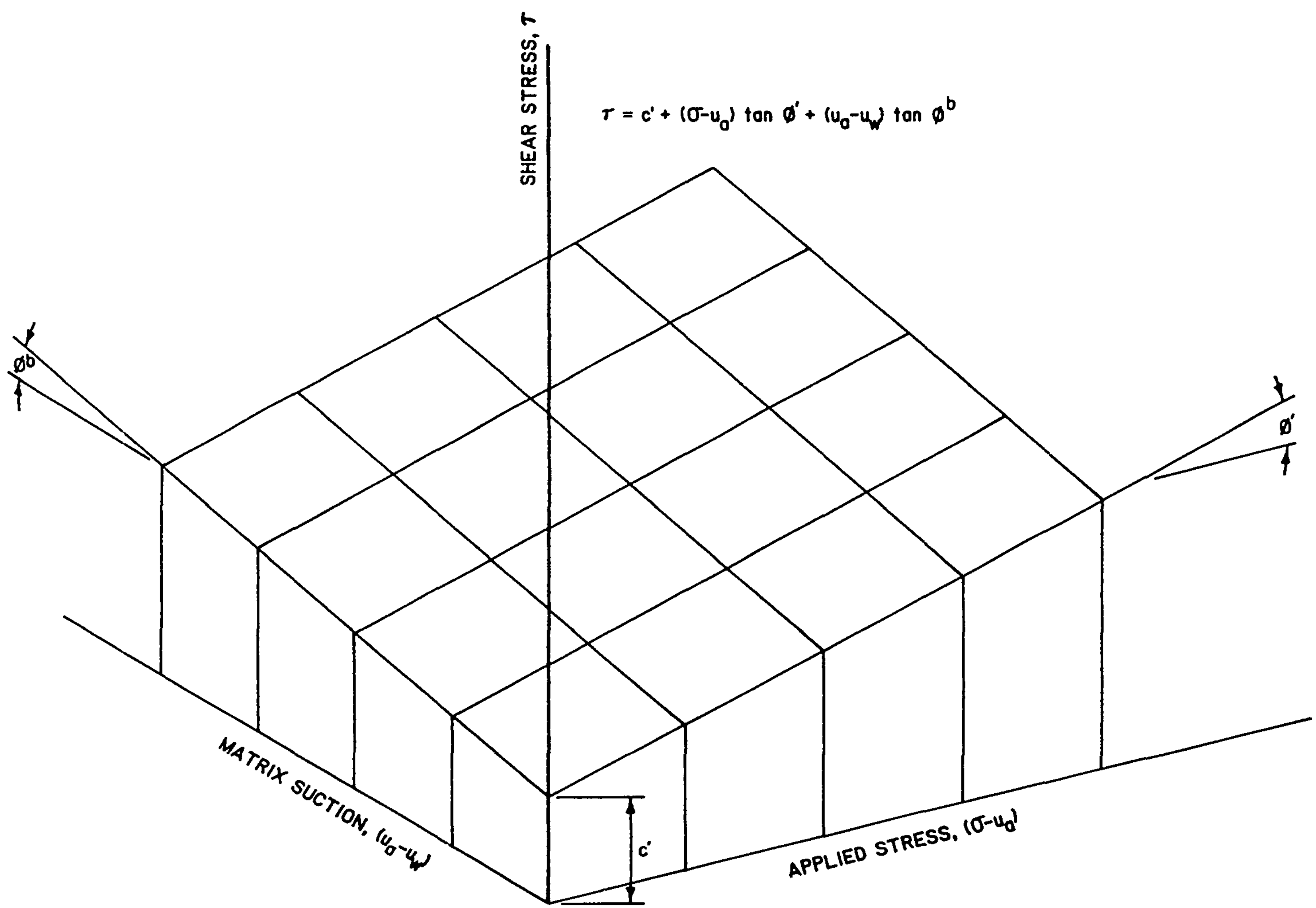

FIG. 4. Extended Mohr-Coulomb strength relationship for unsaturated soils (After Fredlund, 1979).

Table 2. Unsaturated Strength Parameters for Boulder Clay, Compacted Shale and Dhanauri Clay (After Ho and Fredlund, 1982a)

Triaxial Test Type	Soil Type	As Compacted		Apparent Cohesion c'		Friction Due to		Coefficient of Correlation*
		Water Content	Dry Density			Applied Stress ϕ'	Matrix Suction ϕ^b	
		percent	pcf**	tsf	kPa	deg	deg	
Constant Water Content	Boulder Clay†	11.6	----	0.10	9.6	27.3	21.7	0.97
Constant Water Content	Compact-ed Shale†	18.6	----	0.16	15.8	24.8	18.1	0.97
Constant Water Content	Dhanauri Clay††	22.2	98.7	0.16	15.5	28.5	22.6	0.99
		22.2	92.3	0.12	11.3	29.0	16.5	0.97
Consoli-dated Drained	Dhanauri Clay††	22.2	98.7	0.39	37.3	28.5	16.2	0.97
		22.2	92.3	0.21	20.3	29.0	12.6	0.96

* Refers to a linear regression analysis with respect to ϕ^b.
** 100 lb/ft^3 = 1600 kg/m^3.
† After Bishop, Alpan, Blight and Donald (1961).
†† After Gulhati and Satija (1981).

strengths of unsaturated soils appeared to be promising. However, because of a limited data base, uncertainty remained regarding the influence of variables, such as water content, density, degree of saturation and specimen preparation and testing procedures on the shear strengths of unsaturated soils as well as on the measured values of suction. For example, the range of values of the unsaturated strength parameter, ϕ^b, obtained for compacted specimens of Dhanauri clay (Table 2) appeared to be dependent upon the dry density of the specimens and the type of test, i.e. constant water content test or consolidated drained test. Yong, Japp and How (1971) and Yong (1980) reported unique relationships between shear strength, soil suction and dry density for kaolin and St. Rosalie clays. Although hysteric effects due to sorption of water were evident, the multiple valued functions were reduced to a singular surface when the data were expressed in terms of dry density. Turnbull and McRae (1950) presented data which indicated the strengths of unsaturated soils were dependent upon the dry densities and water contents of compacted specimens. Hilf (1975), Lee and Haley (1968), Seed and Chan (1959), and Seed, Mitchell and Chan (1961) have shown that shear strengths of unsaturated soils were affected by compaction water content and the method of compaction. Specimens compacted dry of optimum were stronger, more brittle and tended to swell whereas specimens compacted wet of optimum were weaker, more ductile and tended to consolidate. Specimens molded by dynamic or static compaction were more brittle and tended to swell as compared to specimens molded by kneading compaction. Because of these uncertainties, it was believed that reasonable values for the strength parameter, ϕ^b, could not be anticipated or estimated with any degree of confidence. Therefore, further research was needed.

As a result of the observation that ϕ^b was apparently dependent upon test type, the literature was again perused to identify types of triaxial tests routinely used for testing unsaturated soils. Three tests were identified:

(a) Results of constant water content (CW) tests were reported by Bishop, Alpan, Blight and Donald (1961) and Gulhati and Satija (1981). The cell or chamber pressure, pore air pressure and specimen water content were constant during shear. Volume changes and pore water pressures induced during shear were measured. Generally, the degree of saturation increased as the test was conducted because of a decrease of the specimen volume caused by an increase of normal stresses. The results of these tests indicated that suction decreased as the degree of saturation increased.

(b) Results of consolidated-drained (CD) tests were reported by Gulhati and Satija (1981) and Ho and Fredlund (1982a, 1982b). The cell pressure, pore air pressure and pore water pressure were constant during shear. Specimen volume changes and the volume of water entering or leaving the specimen during shear were measured. Suction remained constant because pore air and pore water pressures were controlled.

(c) Unconsolidated undrained (UU) tests were reported by the U.S. Department of the Interior Bureau of Reclamation (1974). The cell pressure and specimen water content were constant during shear. Pore air pressure, pore water pressure and volume changes induced during shear were measured. As with CW tests, suction generally decreased as the test was conducted because the degree of saturation of the specimens increased as a result of volume changes caused by increased normal stresses.

In summary, the influence of the stress variables, applied stress, $(\sigma - u_a)$, and matrix suction, $(u_a - u_w)$, on the shear strengths of unsaturated soils has been confirmed or inferred by several researchers (Bishop, Alpan, Blight and Donald, 1961; Bishop and Blight, 1963; Blight, 1966; Croney and Coleman, 1961; Dowdy and Larson, 1971; Escario, 1980; Raju and Khemka, 1971; Towner, 1961; Williams and Shaykewich, 1970). Shear strengths of unsaturated soils have been expressed as unique functions of these stress variables as given by Equations 11 or 15. However, little information is available regarding the

influence of water content, density and the degree of saturation on matrix suction and the shear strengths of unsaturated soils. Therefore, reasonable values for unsaturated strength parameters, such as χ or ϕ^b, can not be anticipated with confidence.

Influence of Osmotic Suction on Shear Strength

Lambe (1958) and Lambe and Whitman (1969) used the attractive-repulsive forces concept to demonstrate the importance of osmotic suction for effective stress analysis. They suggested a modified form of the van't Hoff equation which related osmotic pressure to the concentration of ions between and at the edge of adjacent particles. Lambe and Whitman (1969) recommended that the effects of electrical forces on effective stresses should be expressed in the form of Equation 16, where osmotic pressure is equivalent to the repulsive or R forces:

$$\sigma' = \sigma_i \, a = \sigma - a_w \, u_w - (R - A) \tag{16}$$

where

σ_i = intergranular contact stress

a = area soil particle contact ratio, usually less than 0.03

a_w = area water ratio, usually greater than 0.97 in saturated soil

u_w = pore water pressure

R = repulsive stress between particles (Coulombic electrical force)

A = attractive stress between particles (van der Waal force)

Lambe and Whitman indicated the R and A stresses were due to clay particle attraction, cation hydration and osmotic repulsion forces of the clay platelet-water-cation system, although quantitative values were not assigned.

Equation 16 implies that effective stresses should be greatest when the repulsive and attractive stresses are balanced or when the particles are forced close together such that a net attractive force

results. The addition of salts to the pore water would increase osmotic suction and decrease the repulsive stresses, which would also tend to balance the attractive and repulsive stresses.

The influence of electrolytes in the pore fluid of soils has been documented by numerous investigators. Bjerrum and Rosenqvist (1956) sedimented a low plasticity quick clay in an aqueous solution of sodium chloride (NaCl) at a concentration of 35 grams of salt per liter of water (g/l). Following sedimentation, the salt was leached from several specimens. Results of the shear tests indicated the strengths of the salt samples were approximately 75 percent greater than the strengths of the leached samples. Torrance (1974) reported a similar study of the behavior of an undisturbed marine clay. Upon leaching, shear strengths were also reduced. Moum and Rosenqvist (1961) conducted shear tests on specimens of illitic and montmorillonitic clays which had been sedimented in a solution of NaCl at a concentration of 13.5 g/l. After sedimentation, potassium chloride was allowed to percolate through selected specimens. The shear strengths of the K-soils were about 50 percent greater than the shear strengths of the Na-soils. Sridharan, Rao and Rao (1971) found that the shear strength parameters c' and ϕ' for montmorillonitic and kaolinitic clays increased following the addition of divalent calcium hydroxide to the soil.

These investigations, as well as studies by other researchers (Dowdy and Larson, 1971; Ladd and Martin, 1967; Low, 1968; Morgenstern and Balasubramonian, 1980; Olson, 1963; Olson and Mitronovas, 1962; Peter, 1979; Sridharan and Rao, 1979, 1973, 1971), infer that the engineering behavior of clay soils is dependent upon the type of salt in the pore fluid and its concentration. However, few comprehensive investigations to assess the influence of osmotic suction on the shear strengths of unsaturated soils have been reported.

Summary

Based upon a review of the literature, the strengths of unsaturated soils appeared to be dependent upon numerous variables including compaction water content, dry density, method of compaction and the

type and concentration of electrolytes in the pore fluid. The effects of capillarity or matrix suction may be dominant in unsaturated samples of sands, silts and low plasticity clays. For higher plasticity clays, such as illites and montmorillonites which have considerable suction forces derived from clay particle attraction and cation hydration, capillarity may be of secondary significance. Therefore, comprehensive laboratory investigations are needed to evaluate the influence of these and other variables on the strengths of unsaturated soils and to develop appropriate models to describe the shear strengths of unsaturated soils.

RESEARCH PLAN

Following a review of the literature, a laboratory investigation was conceived and executed to assess the influence of soil suction on the shear strength of unsaturated soil. The effects of three variables were isolated and studied: compaction water content, density and treatment of the soil with potassium chloride. Suction was measured during the tests on unsaturated specimens to permit an assessment of unsaturated strength parameters, such as χ or ϕ^b. These parameters, in turn, allowed the influence of suction on the shear strength of unsaturated soil specimens to be evaluated. Constant water content tests were selected because the effects of density variation could be evaluated more easily than for results obtained from consolidated drained tests in which both density and water content changes could occur simultaneously.

To assess the influence of compaction water content on matrix suction as well as on the shear strengths of unsaturated specimens, triaxial compression tests were conducted on specimens which had been compacted at nominal water contents of 20 to 21 percent and 26 to 27 percent. These water contents were 3 to 4 percentage points dry and wet of optimum water content, respectively.

To assess the effects of dry density on suction and shear strengths of unsaturated soil, replicate specimens were compacted at nominal water contents of 20 or 27 percent. Specimens were then subjected to selected consolidation and rebound stresses prior to shear. The first group of specimens was isotropically consolidated by stresses of 0.7, 1.4, 2.9, 5.8 or 11.5 tsf (70, 140, 280, 550 or 1100 kPa) prior to shear. The second group of specimens was consolidated by 2.9 tsf (280 kPa) and rebounded against 1.4 or 0.7 tsf (140 or 70 kPa) before the shear phase was conducted. The third group of specimens was consolidated by 11.5 tsf (1100 kPa) and rebounded against 5.8, 2.9, 1.4 or 0.7 tsf (550, 280, 140 or 70 kPa) prior to shear.

To investigate the influence of osmotic or solute suction on the shear strengths of unsaturated soil, selected specimens were treated with potassium chloride prior to compaction. Prior to shear, these

specimens were isotropically consolidated by stresses of 0.7, 1.4, 2.9, 5.8 or 11.5 tsf (70, 140, 280, 550 or 1100 kPa). To evaluate the influence of osmotic suction on shear strengths, the test results were compared with the test results for untreated specimens. Potassium chloride was used to treat the clay because the partial vapor pressure of an aqueous solution of this salt was unaffected by subtle temperature fluctuations (Washburn, 1928) which typically occur in the soils laboratory environment.

To provide a reference for evaluating the shear strengths of unsaturated specimens, back pressure saturated triaxial specimens were tested. Specimens were compacted at nominal water contents of 20 and 27 percent. Selected specimens were isotropically consolidated by stresses of 2.9 or 11.5 tsf (280 or 1100 kPa) prior to shear. A second group of specimens was consolidated by 2.9 tsf (280 kPa) and rebounded against 1.4, 0.7 or 0.4 tsf (140, 70 or 30 kPa) before the shear phase was conducted. A third group of specimens was consolidated by 11.5 tsf (1100 kPa) and rebounded against 5.8, 2.8, 1.4 or 0.7 tsf (550, 280, 140 or 70 kPa) before the specimens were sheared.

Several methods were available to normalize the effects of density on the strengths of soil (Atkinson and Bransby, 1978; Hvorslev, 1961, 1969; Ladd, 1971). Following a brief review of each, Hvorslev's "true friction, ϕ_e - true cohesion, C_e" concept was selected. Although Hvorslev stated his model was valid only for saturated soil behavior, it was assumed that Hvorslev's model was applicable to unsaturated soil behavior as well. This assumption was based upon the belief that Hvorslev expressed the normalized shear strengths in terms of the water content of the specimens at failure because of the ease of determining this parameter as compared to density or void ratio. Furthermore, it had been observed frequently that the unconfined compression strengths of compacted specimens were dependent upon the density of the specimens.

Hvorslev's strength parameters may be obtained by comparing the strengths of normally consolidated and overconsolidated specimens at the same void ratio at failure, as illustrated conceptually in Figure 5a by points a and b, respectively. However, due to the difficulty

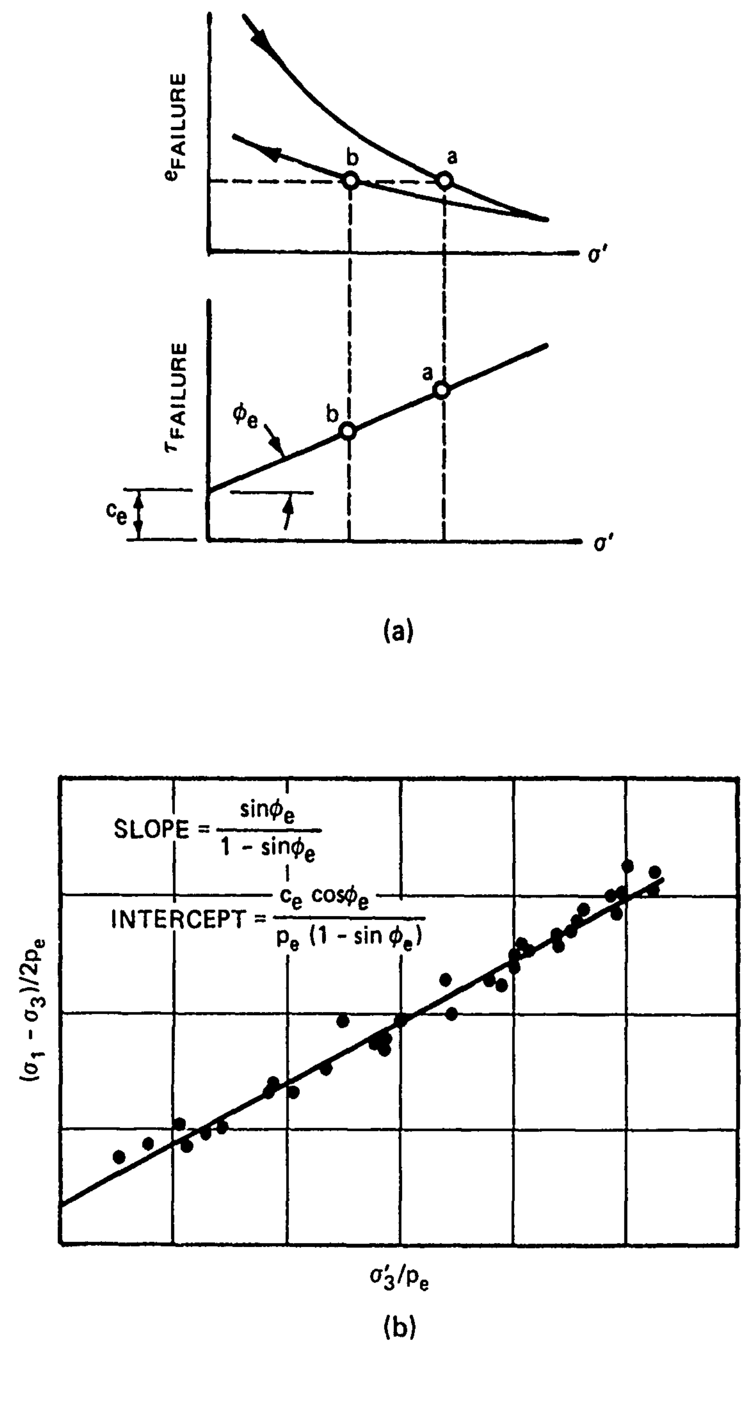

FIG. 5. Determination of Hvorslev's "true friction - true cohesion" strength parameters (After Bishop and Henkel, 1962). (a) Strength parameters determined using normally consolidated and overconsolidated specimens sheared with identical void ratios at failure. (b) Normalizing technique using an "equivalent consolidation pressure".

of obtaining test results for normally consolidated and overconsolidated specimens which have identical void ratios at failure, Bishop and Henkel (1962) proposed a normalizing technique which is illustrated in Figure 5b. The method consisted of dividing the shear stress and the normal stress by an "equivalent consolidation stress", P_e. Bishop and Henkel defined P_e as the consolidation pressure or stress which produced a particular water content (or void ratio) in a saturated, normally consolidated specimen. True friction and true cohesion were related to the slope and intercept of the strength envelope as indicated by the equations shown in Figure 5b.

To aid in the selection of a P_e relationship, one dimensional consolidation tests were conducted on specimens compacted at nominal water contents of 20 and 27 percent. For each series of tests, one specimen was tested at the "as compacted" or natural water content condition. The other two specimens were inundated and subjected to initial boundary conditions imposed by the swell and swell pressure tests, which are described in Engineer Manual EM 1110-2-1906 (Department of the Army, Office of the Chief of Engineers, 1970) and ASTM Standard D-4546 (American Society for Testing and Materials, 1989). The maximum consolidation stress which was applied to any specimen was 128 tsf (12.3 MPa), although several specimens were rebounded from lower maximum stresses because soil was extruded around the top loading platen. Suction was measured as tests were conducted on the natural water content specimens.

MATERIALS AND TEST METHODOLOGY

Soil

Vicksburg buckshot clay was selected for the investigation because it was locally available and a substantial amount of test data had been reported (Brabston, 1981; Donaghe and Townsend, 1975; Horz, 1983; Molina, 1960; Peters, Leavell and Johnson, 1982; Strohm, 1966). Furthermore, osmotic suction for this soil was negligible which minimized the uncertainty of assessing the influence of matrix and osmotic suction on the unsaturated strength parameters.

Vicksburg buckshot clay is a brown plastic clay (CH) with a trace of sand (Department of the Army, Office of the Chief of Engineers, 1970; U.S. Army Engineer Waterways Experiment Station, 1960). Ninety-seven percent of the soil by dry weight passes the No. 200 U.S. Standard Sieve (0.074 mm.) and 43 percent is finer than 0.002 mm. The specific gravity (G_s) is 2.72 and the Atterberg limits are liquid limit (LL) = 56 percent, plastic limit (PL) = 21 percent and plasticity index (PI) = 35 percent. The electrical conductivity of an extract of the pore fluid obtained by the saturation extract technique was 0.3 millimhos per centimeter (mmho/cm). From this value, solute suction was calculated as 0.1 tsf (10 kPa) (Black, 1965; Richards, 1954). The grain size distribution, specific gravity and Atterberg limits for buckshot clay are presented in Figure 6.

Testing Equipment

Suction Measurement

Important considerations for selecting a device for measuring suction included attention to the accuracy of the apparatus for the ranges of suction anticipated during the investigation and the ease of modifying conventional laboratory testing equipment and procedures for use of the suction measuring apparatus. Although apparatuses such as tensiometers, vacuum desiccators, electrical resistance blocks and filter paper (Bocking and Fredlund, 1979; Lam, 1980; Murthy, Sridharan and

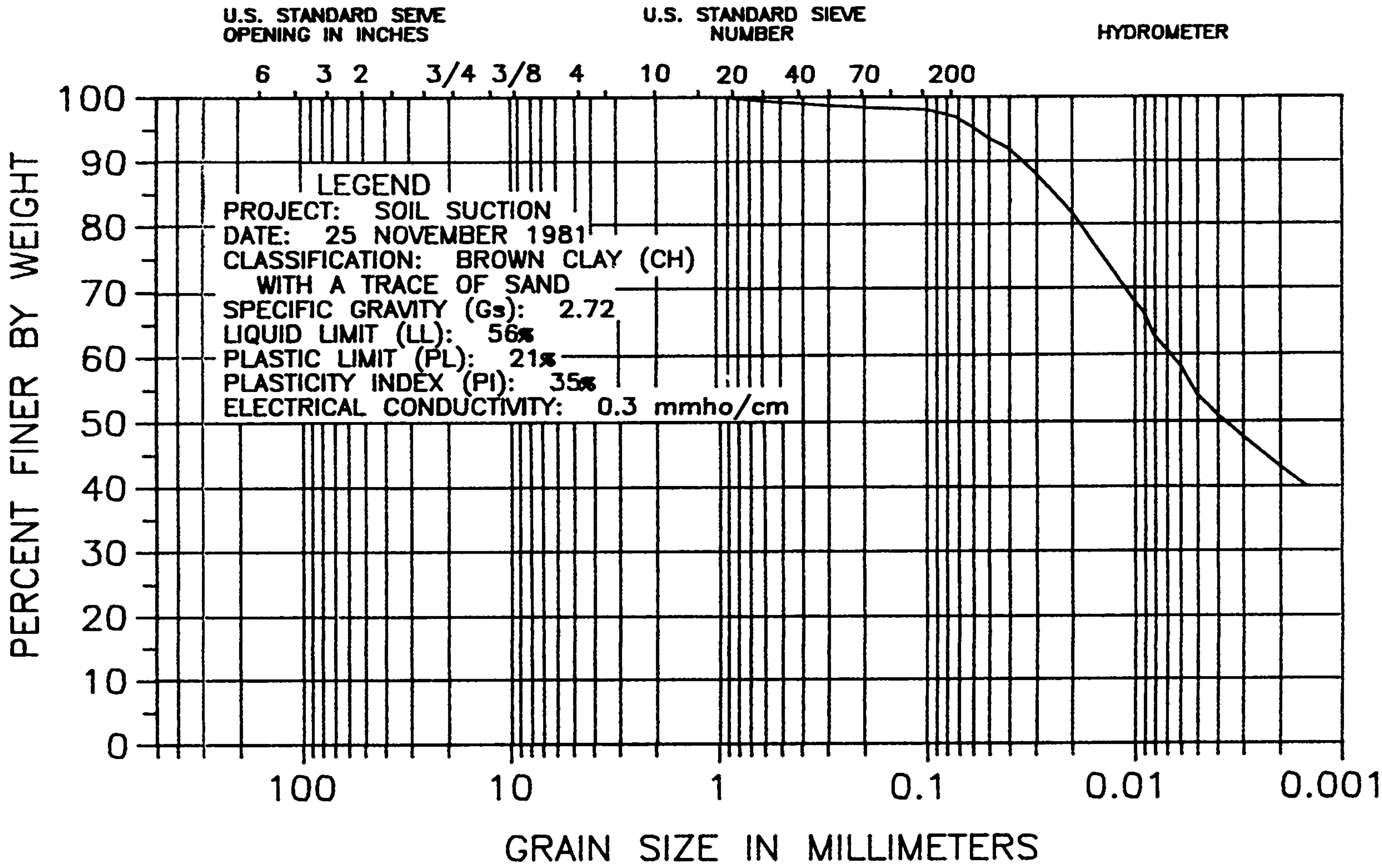

FIG. 6. Physical properties of buckshot clay.

Nagaraj, 1987; Snethen and Johnson, 1980) could be adapted to laboratory testing equipment, the most common devices for measuring soil suction during triaxial tests were the pressure plate apparatus (Bishop and Henkel, 1962; Fredlund, 1975; Gulhati and Satija, 1981; Hilf, 1956; Ho and Fredlund, 1982b; Lam, 1980; U.S. Department of the Interior Bureau of Reclamation, 1966) and the thermocouple psychrometer (Edil, Motan and Toha, 1981; Johnson, 1974a; Morrison, 1980).

Generally, pressure plate apparatuses have performed satisfactorily when matrix suction stresses were less than approximately 15 tsf (1.4 MPa), i.e. low plasticity clays, silts and sandy clays. Unfortunately, the pressure plate device cannot be used to measure osmotic suction stresses. As a matter of comparison, psychrometers cannot be used to measure low values of suction accurately but have been used successfully to measure suction stresses as large as 80 to 100 tsf (7.7 to 9.6 MPa) (Brown and Thompson, 1977; Hamilton, Daniel and Olson, 1981). Psychrometers can be used to measure total or osmotic suction stresses, although independent measurements of total and osmotic suction stresses are required to evaluate matrix suction. A review of pressure plate apparatuses and thermocouple psychrometers is presented in the following paragraphs.

Pressure plate apparatus. Pressure plate apparatuses have been used extensively to measure matrix suction, which is the algebraic difference between the measured values of pore air and pore water pressures, as given by Equation 7:

$$h_m = u_a - u_w \tag{7}$$

In principle, a saturated high air entry (high bubbling pressure) porous plate is used to separate an unsaturated soil specimen from a container of water. As the capillary or suction stress in the soil specimen draws water through the porous plate, the absolute pressure of the water in the container is reduced. To prevent cavitation, air pressure is simultaneously applied to the soil specimen and the porous plate. This causes the pore water pressure in the soil specimen to increase.

The procedure, which is known as the axis translation technique (Hilf, 1956), is illustrated in Figure 3.

A conventional triaxial apparatus which has been designed to conduct tests on saturated specimens can be easily modified to test unsaturated soils. A high air entry pressure plate can be substituted for one of the coarser porous stones located in the top or bottom platen. The triaxial device must also be modified to permit independent measurements of pore air and pore water pressures. Figure 7 is a conceptual illustration of a soil specimen in a triaxial apparatus which has been modified to test unsaturated soils using the pressure plate technique.

Three problems or difficulties of conducting tests on unsaturated soils using the pressure plate technique have been identified:

(a) The magnitude of suction must be known or estimated in advance of the test to aid in the selection of the air entry value of the pressure plate. If the air entry value is too high, the permeability of the pressure plate will control the rate of testing. Conversely, if the air entry value is too low, air will readily pass through the pressure plate. This will cause incorrect measurements of the pore water pressure.

(b) As the test is conducted, air will diffuse through the high air entry stone and into the pore water pressure measurement system. As diffusion occurs, water will be displaced and forced into the soil specimen which could alter the engineering properties of an unsaturated soil specimen. To minimize problems caused by air diffusing through the high air entry stone, Fredlund (1975) designed a flushing system to remove the air from the pore water cavity; an inverted burette was used to account for drainage of water from the system or specimen.

(c) The third difficulty of using the pressure plate apparatus may be encountered when the soil specimen is placed in contact with the saturated plate as the test apparatus is assembled. As a result of suction, water tends to flow into the soil specimen, negative pressure in the pore water cavity tends to develop and the initial conditions of the soil specimen begin to change. To minimize the potential problems,

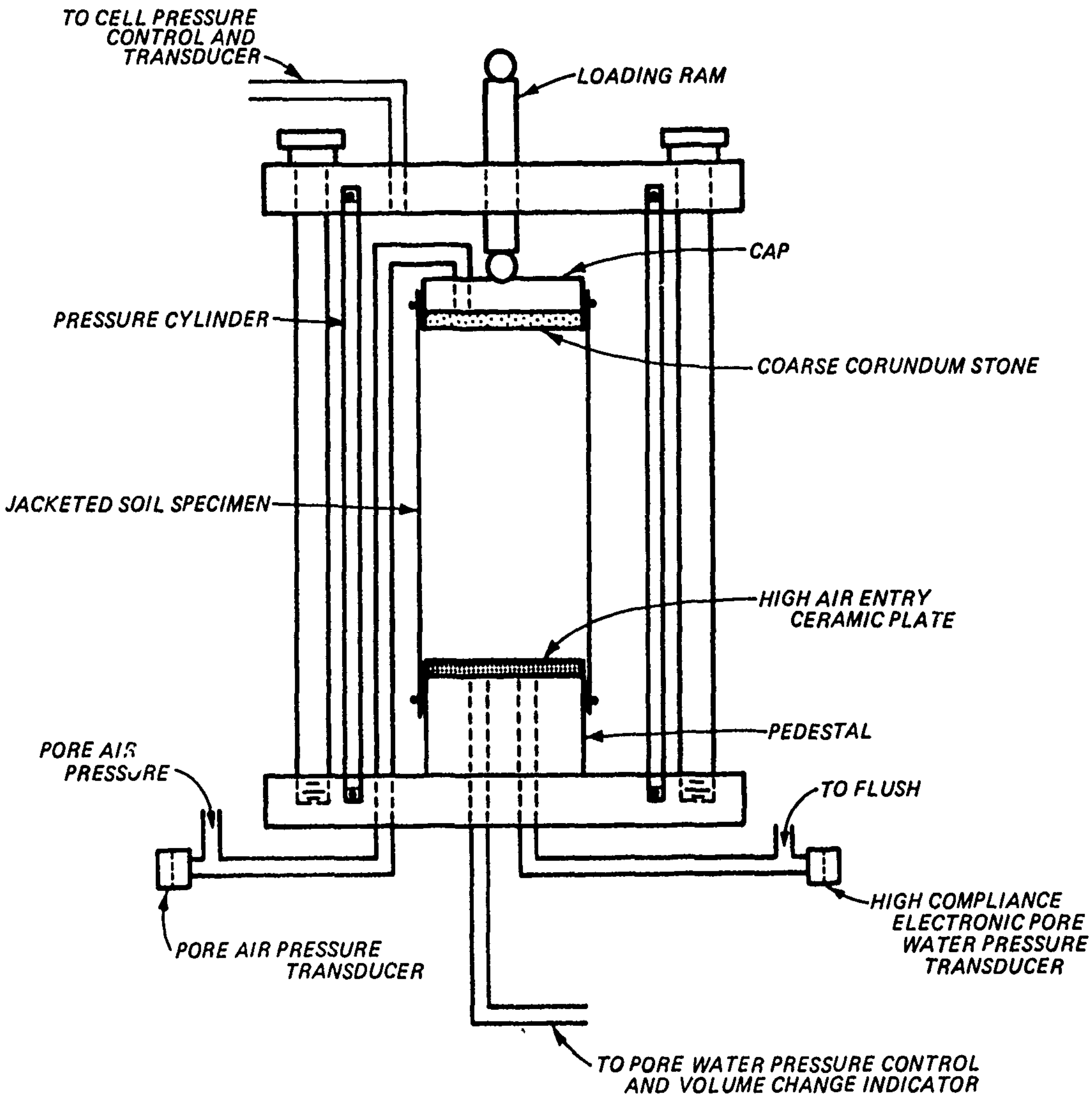

FIG. 7. Triaxial cell for testing unsaturated soils (After Ho and Fredlund, 1982a, 1982b).

it is imperative that the test apparatus is assembled as rapidly as possible. To prevent cavitation of the water in the pore pressure measurement system, the U.S. Bureau of Reclamation (Young, 1984) developed a plunger which could be used to manually increase the pressure in the pore water cavity as the triaxial device was assembled.

Thermocouple psychrometer. The principle of operation of the thermocouple psychrometer is based upon the Peltier cooling effect (Shortley and Williams, 1965). As an electrical current is passed through a circuit of two dissimilar metals, one of the junctions tends to become warmer and the other junction tends to become cooler. With the current flowing in the proper direction, a bead of water condenses on the thermocouple junction of the psychrometer when the temperature reaches the dew point temperature. After the cooling current is terminated, the temperature difference is maintained until the bead of water has evaporated. This temperature difference causes an electromotive force (emf) which is directly proportional to the temperature difference, as given by Equation 17 (Dyke, 1954; Benedict and Hoersch, 1981):

$$E = \alpha\ \delta t \tag{17}$$

where

E = electromotive force, μvolt

α = thermoelectric power, μvolt/deg C

δt = temperature difference, deg C

By comparing the emf measured by a psychrometer in the air above a salt solution of known concentration to the emf when the psychrometer is placed in an unsaturated soil specimen, suction may be inferred.

A schematic drawing of a psychrometer is illustrated in Figure 8. Table 3 illustrates typical relative humidity versus suction relationships for various concentrations of aqueous solutions of potassium chloride (Washburn, 1928). Figure 9 shows typical calibration curves obtained for several thermocouple psychrometers (Johnson, 1974a). Figure 10 is a photograph of thermocouple psychrometers which have been inserted into a soil specimen through the membrane.

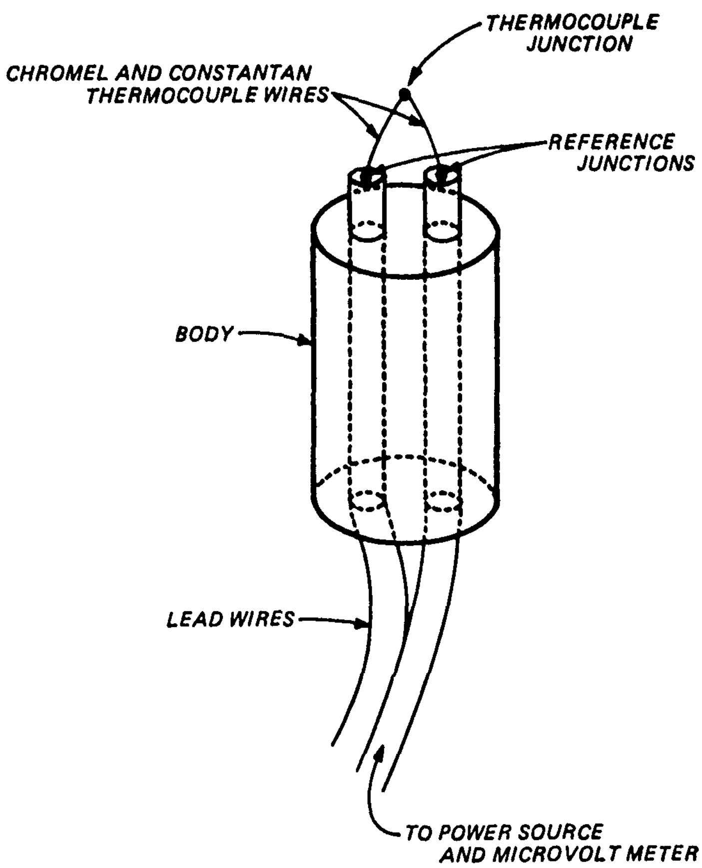

FIG. 8. Schematic diagram of a thermocouple psychrometer.

Table 3. Relative Humidity-Total Suction Relationships
for Selected Concentrations of Potassium Chloride Solutions
(After Washburn, 1928)

Gram Formula Weight per 1000 g of Water M	Relative Humidity percent	Total Suction* tsf	Total Suction* MPa
0.05	99.83	2.4	0.23
0.1	99.67	4.7	0.46
0.2	99.36	9.2	0.88
0.5	98.41	23.0	2.21
1.0	96.84	46.1	4.42
1.5	95.26	69.8	6.69
2.0	93.68	93.8	8.99

* Calculated using Equation 5 at 25 deg C and standard atmospheric pressure.

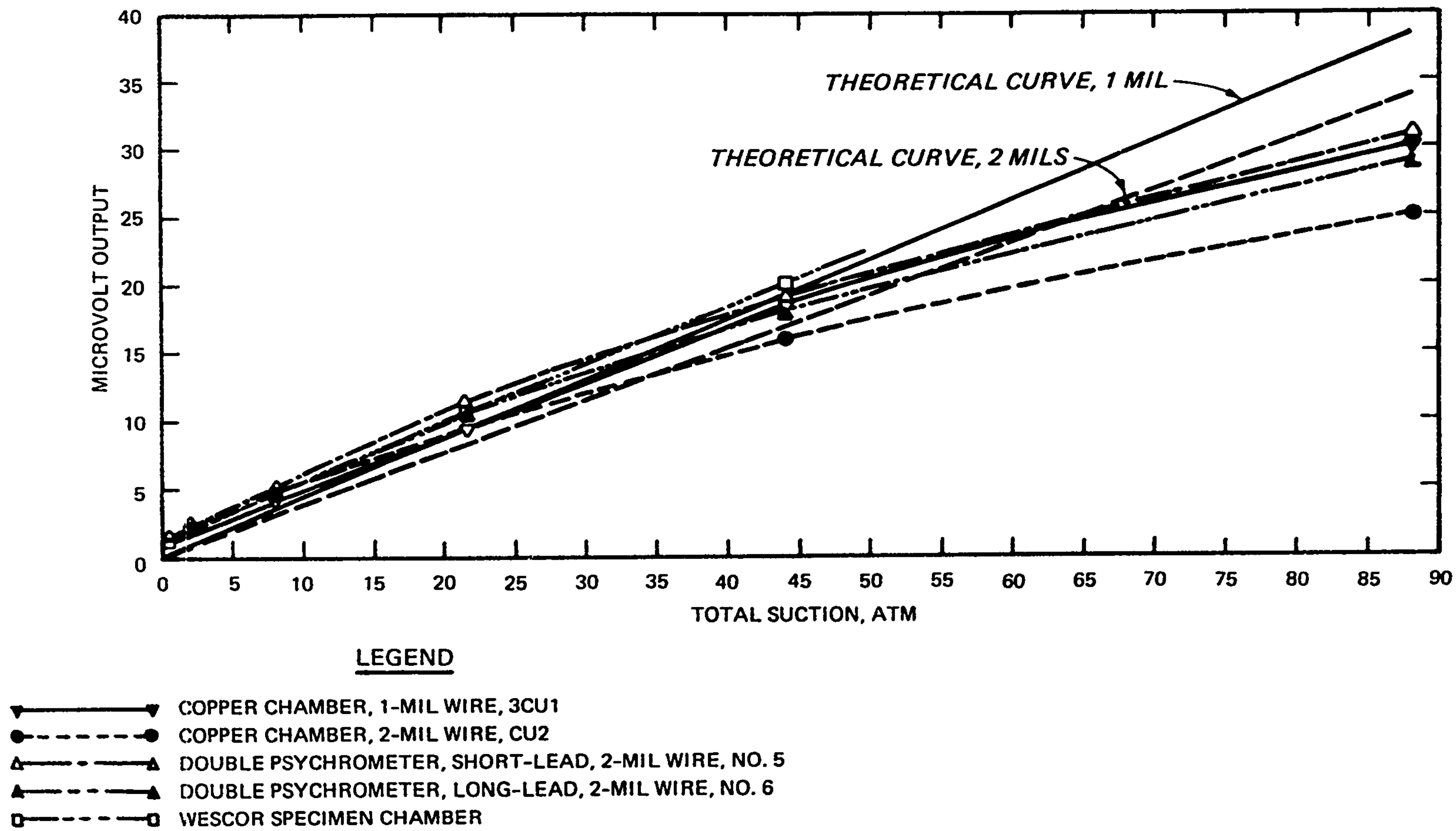

FIG. 9. Typical emf versus suction relationships for thermocouple psychrometers (After Johnson, 1974a).

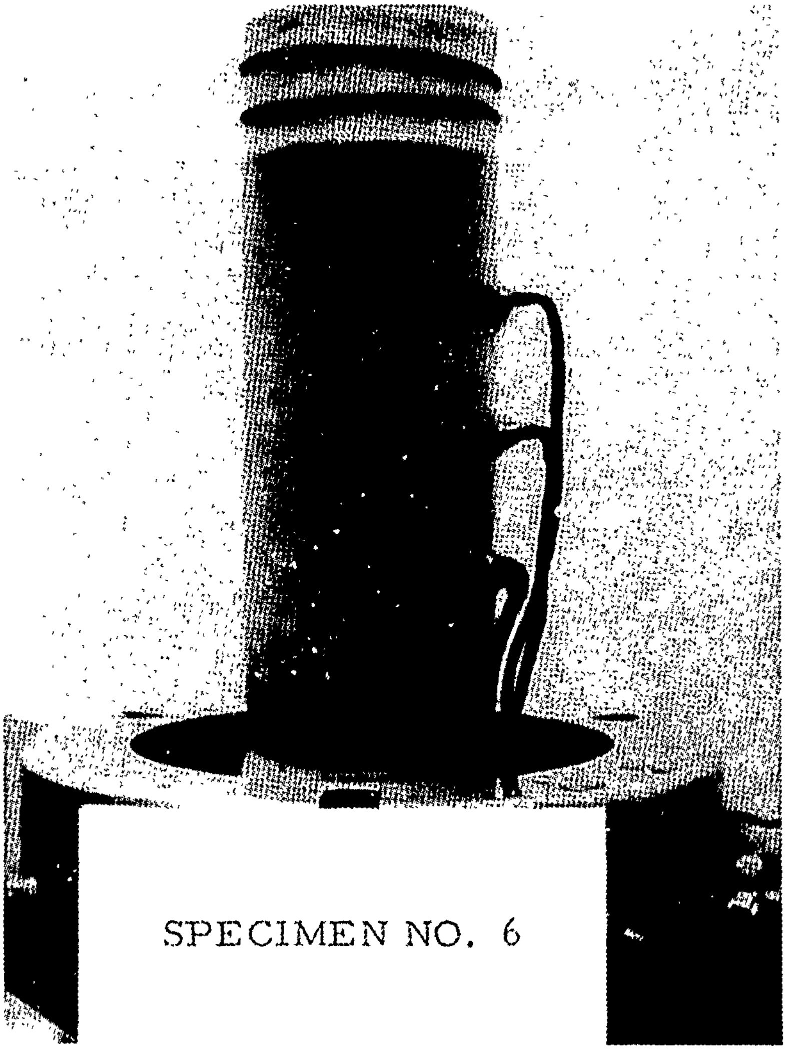

FIG. 16. Apparatus for measuring total suction (After Johnson, 1974b).

Several problems may be encountered when using a psychrometer to measure soil suction. The list includes errors of measurement of the emf caused by temperature effects, ambient electrical signals and corrosion of the thermocouple wires (Daniel, Hamilton and Olson, 1981). A discussion of each of these problems is presented in the following paragraphs:

(a) From Equation 5, it may be observed that suction is directly proportional to the absolute temperature and the logarithm of the relative humidity. Provided that reasonable care is exercised to ensure that all calibrations and tests are conducted at constant ambient temperatures, such as usually encountered in the laboratory environment, several researchers (Daniel, Hamilton and Olson, 1981; Johnson, 1974a) have reported that measured values of emf can be adjusted to an equivalent emf at 25 deg C:

$$E_{25} = E_t/(0.027t + 0.325) \tag{18}$$

where

E_{25} = equivalent emf at 25 deg C, μvolt

E_t = emf at test temperature, μvolt

t = test temperature, deg C

However, if the temperature and relative humidity of the air at the thermocouple junction have not equilibrated with the conditions of the soil specimen, measured values of emf, or suction, could be erroneous. For example, temperature fluctuations near heating and air conditioning ducts could result in erroneous suction measurements because of thermal gradients.

(b) The psychrometer may be sensitive to ambient electrical signals or noises. Unless precautions are taken to ensure adequate grounding and shielding of the system, the effects of ambient signals could have a detrimental effect on test results. For example, the ambient electrical noise produced by fluorescent lights, which is of the order of millivolts, could adversely affect the emf from the psychrometer, which is of the order of microvolts.

(c) Corrosion on the thermocouple, the variation of time during which the cooling current is applied to the psychrometer and the magnitude of the applied cooling current could seriously affect results. Although these problems have not been adequately addressed in the literature, precautions should be taken to minimize the effects of these variables. The psychrometer should be inspected and cleaned prior to each test and replaced as necessary. Care should be exercised to ensure that calibration and test procedures are identical and rigorously practiced.

The problems of obtaining reliable suction measurements with the psychrometer should be apparent. Although suction stresses are frequently much larger than stresses recorded during conventional geotechnical laboratory testing, it is desirable to measure suction and applied stresses to the same precision and accuracy, i.e. to the nearest 0.1 tsf (10 kPa). Unfortunately, this may not be an easy task. For example, to measure suction to the nearest 0.1 tsf (10 kPa), the emf must be recorded to the nearest 0.05 μvolt. For the sake of comparison, the electrical signal from conventional testing equipment, such as pressure transducers, would be of the order of 0.05 volt for comparable stresses. Therefore, special laboratory techniques and procedures, such as shielding and grounding the test apparatus and conducting tests in a controlled temperature environment, may be required to obtain satisfactory data.

Development of Laboratory Testing Equipment

Based upon a review of the research plan, an assessment of suction measuring equipment, and a few preliminary suction tests conducted on compacted specimens of Vicksburg buckshot clay, laboratory equipment was modified to test unsaturated soils. The thermocouple psychrometer was selected to measure suction because preliminary tests indicated that suction stresses in unsaturated specimens of buckshot clay were fairly large and could possibly exceed 10 to 15 tsf (1.0 to 1.4 MPa). These large values of suction were of the same magnitude as the maximum air entry values for pressure plates which were available. Furthermore, it was decided the psychrometer method for measuring suction was

more versatile than the pressure plate method because total and osmotic suction stresses could be measured with the same device.

Only minor modifications to conventional laboratory soils testing equipment were required to test unsaturated soils. A fixed ring consolidometer was modified to allow a psychrometer to be inserted into the top loading platen to measure suction in unsaturated specimens during consolidation tests. Two modifications to the triaxial apparatus were required. First, a thermocouple psychrometer was inserted into the soil specimen through the base platen of the device. Second, a double barrel chamber was designed and fabricated which would permit an assessment of the volume change of unsaturated soils subjected to triaxial compression. The volume of water which flowed into or out of the inner chamber during the test could be related to the change of volume of the unsaturated specimen.

Thermocouple psychrometer. In the interest of causing minimal adverse affects on the behavior of the soil specimen, a 0.04 in. (0.16 cm.) diameter psychrometer, which used 0.001 in. (0.002 cm.) diameter Chromel and constantan wires for the thermocouple, was fabricated at the U.S. Army Engineer Waterways Experiment Station (WES). Conceptually, this psychrometer would be inserted into a 1/8 in. (0.3 cm.) diameter stainless steel tube which had been placed within the specimen as the soil was compacted. However, after numerous attempts to calibrate the psychrometer, it was concluded that an acceptable calibration could not be obtained. The WES psychrometer was discarded and replaced by a commercially manufactured psychrometer.

Although an acceptable calibration of the WES psychrometer was never obtained, two important lessons were learned: ambient temperatures and the time increment which the cooling current was applied to the psychrometer had to be carefully controlled. During an attempt to calibrate the WES psychrometer in the air above a 1.0 M KCl solution, it was observed that values of emf, which had been corrected to 25 deg C using Equation 18, varied approximately 5 percent/deg C. For example, when the cooling current was applied to the psychrometer for 30 seconds, the corrected value of emf increased from 11.6 μvolt at an

ambient temperature of 16.2 deg C to 14.2 μvolt at a temperature of 21.2 deg C. Furthermore, it was observed that as the cooling current was applied to the psychrometer for longer periods of time, the rate of change of the measured values of emf decreased from about 6 μvolt per minute per logarithmic cycle of time for the first two minutes to an asymptotic condition after about two hours. For example, the measured value of emf was approximately 12.5 μvolt when the cooling current was applied for 15 seconds. When the cooling current was applied for 30 seconds, the emf increased to 14.0 μvolt. The emf increased to 15.5 μvolt when the cooling current was applied for 60 seconds. When the current had been applied for two hours, the emf was 21.5 μvolt.

A commercially manufactured thermocouple psychrometer which used 0.001 in. (0.002 cm.) diameter Chromel and constantan wires was selected to replace the WES psychrometer. Calibrations of the commercial psychrometers were fairly repeatable although the measured values of emf were somewhat sensitive to the length of time which the cooling current was applied. Typically, the emf increased at a rate of 1.5 μvolt per minute per logarithmic cycle of time the first two minutes in which cooling current was applied. However, tests were never conducted to determine the influence of temperature on the measured emf because a decision had been made to construct a constant temperature water bath to house the triaxial devices.

As the first commercial psychrometer was being calibrated, it was observed that external or ambient electrical signals apparently affected the emf readings. For example, the measured values of emf increased slightly as the operator's hands approached the electrical wires connecting the psychrometer and the data acquisition system. To minimize this problem, a shielding and grounding system was devised. The psychrometer wires were placed in copper tubing and a large copper plate was placed on the floor for the operator to stand on while working near the test device. The testing facility, including the triaxial devices, instrumentation and the copper plate were attached to a grounding rod located outside of the laboratory. After the shielding and grounding system was completed, it was noted that measured values of emf could be

reproduced to the nearest 0.2 μvolt which corresponded to a suction of 0.5 tsf (50 kPa).

A typical calibration curve for the psychrometers used during this investigation is presented in Figure 11. Figure 12 is a photograph of two of the psychrometers used during the study. Note that the ceramic housing which protects the thermocouple junction has been removed from the psychrometer shown on the left side of the photo. Prior to testing, the psychrometer was placed in a specially designed housing. Both the psychrometer and the housing were then inserted into the soil specimen for testing.

Volume change apparatus. The volume of water expelled from a saturated specimen during a triaxial test can be used as a direct measurement of the volume change of the specimen itself. However, for tests on unsaturated specimens special devices must be used to measure volume changes. Two general techniques for measuring the volume change of unsaturated soil specimens are available: lateral sensors for measuring radial deformations (Al-Hussaini, 1981) and single (Johnson, 1974a) or double barrel cylinders (Bellotti, Bizzi and Ghionna, 1982) for measuring volumetric deformations. Although extensive efforts have been expended to perfect lateral sensors for use during triaxial testing, questions usually arise regarding the interpretation of test results. For example, a typical question may be whether the sensor was responding to a depression in the periphery of a test specimen or to the actual deformation of the specimen. Consequently, one must decide the quality of the data. Similarly, when the double barrel cylinder technique is employed, care is required to ensure that the chamber is fully saturated and that creep in the test chamber is minimal.

For the investigation reported herein, a double barrel chamber was designed to measure the stress-volume change relationships of unsaturated soils. As envisioned, equal pressures would be applied to the annular cavity located between the soil specimen and the inner chamber and to the cavity between the inner and outer chambers. Provided the cavity between the soil specimen and the inner chamber was saturated,

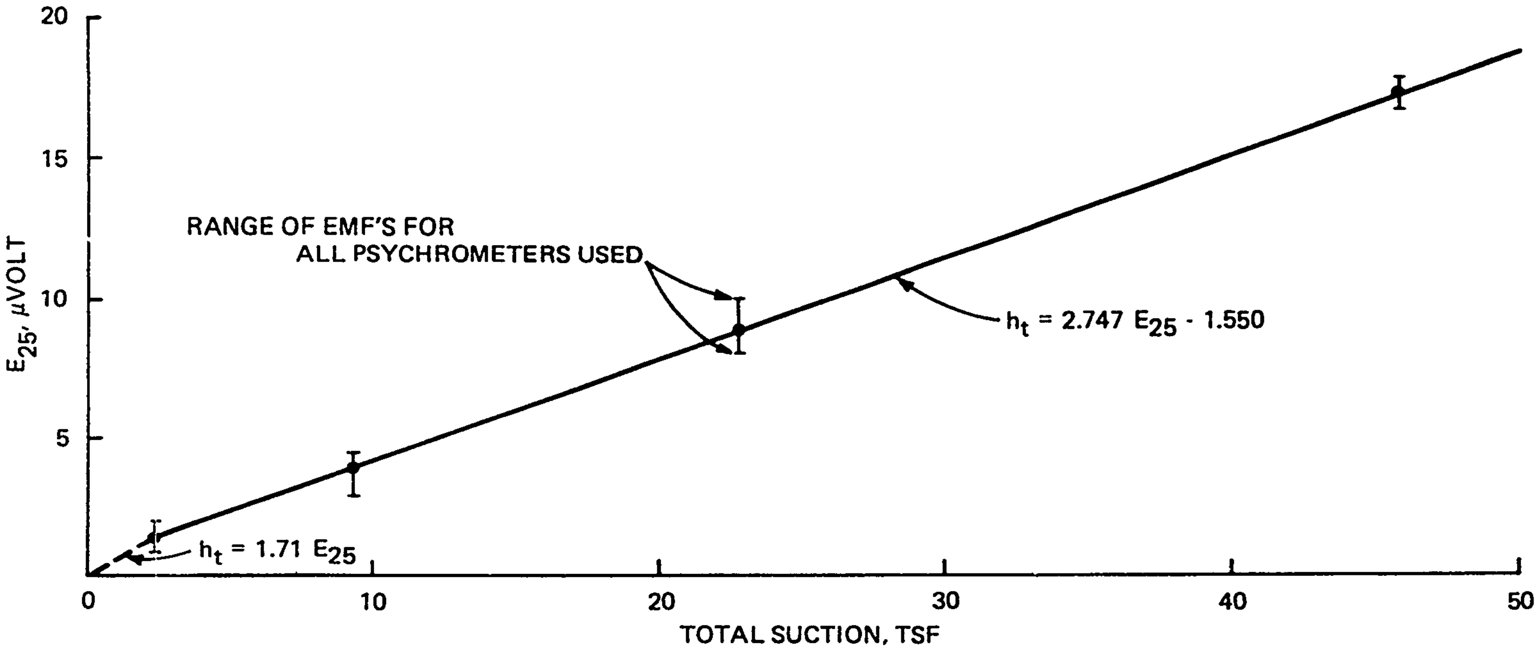

FIG. 11. Typical calibration curve for psychrometers used in the investigation reported herein.

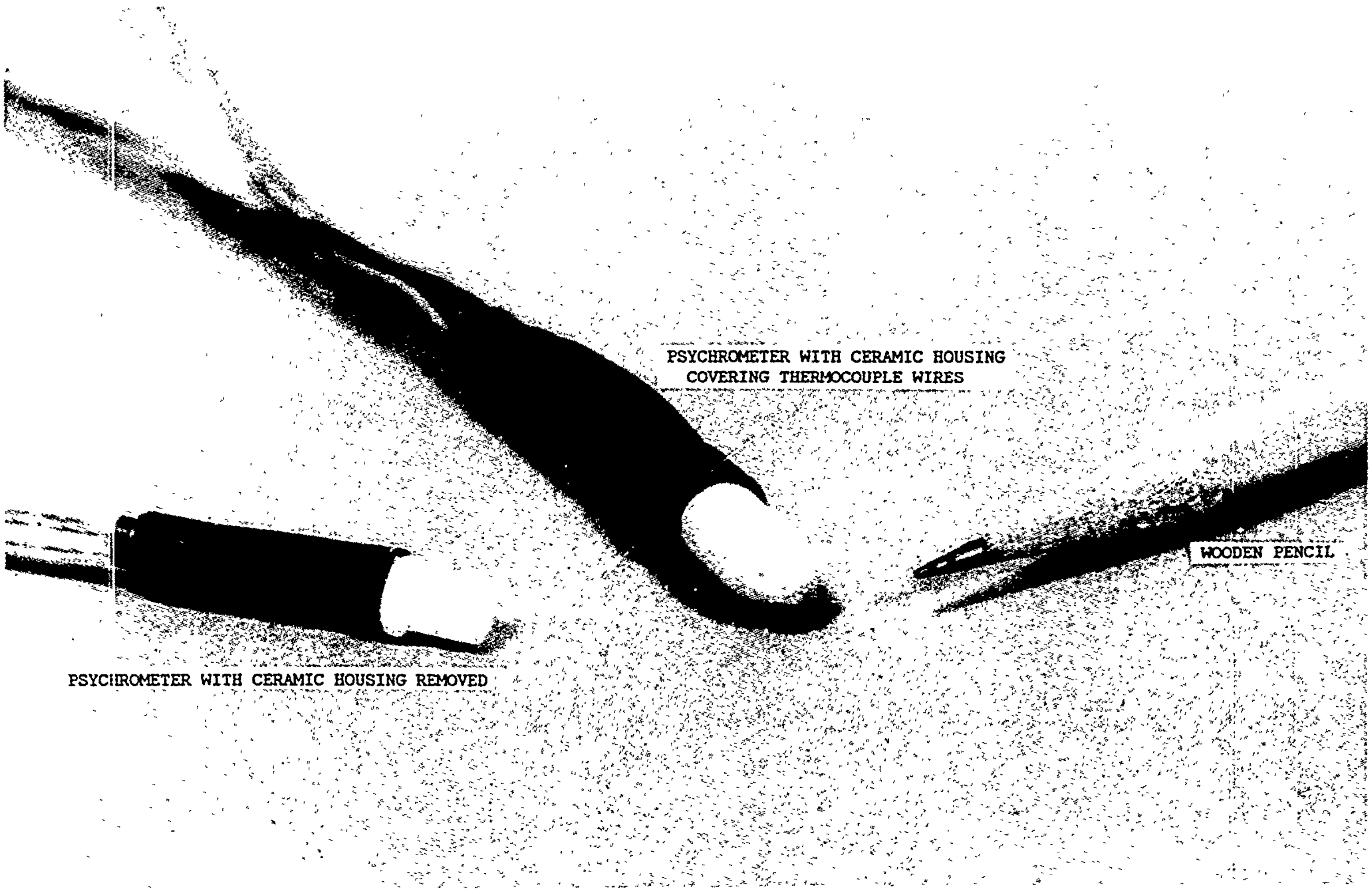

FIG. 12. Two psychrometers used during the investigation.

volumetric strains of the unsaturated soil specimens could be calculated from the volume of water expelled from the inner barrel, which is similar to the technique used for the calculation of volumetric strains for saturated specimens.

The first inner barrel was constructed of an acrylic material. Because equal pressures were applied to each side of the inner barrel, it was anticipated that creep would be negligible. However, this apparently was not the case as a repeatable pressure versus volume change relationship could not be obtained. Guided by this experience, an inner barrel was constructed of aluminum. Provided that reasonable care was taken to saturate the inner barrel, a repeatable correction factor was obtained for pressure effects, i.e. compressibility of the water in the chamber, seating of o-ring seals, etc. The correction factor was 3.7 ml for an increase of the chamber pressure from 0.1 to 0.7 tsf (10 to 70 kPa). For chamber pressures ranging from 0.7 to 11.5 tsf (70 to 1100 kPa), the correction factor was 7.8 ml per logarithmic cycle of pressure. When the chamber pressure was decreased from 2.9 or 11.5 tsf (280 or 1100 kPa) to 0.7 tsf (70 kPa), the correction factor was 1.5 ml per logarithmic cycle of pressure.

To saturate the inner barrel, a differential vacuum was simultaneously applied to the unsaturated soil specimen and to the inner chamber. Approximately two hours elapsed before deaired water, which contained less than 2 parts per million (ppm) dissolved air, was introduced to the system. Although the degree of saturation of the volume change apparatus could not be evaluated easily, a similar procedure had been used to saturate numerous soil specimens with small or negligible back pressures. For example, using the differential vacuum procedure, the clay specimens for the study reported herein were saturated by back pressures less than 1 tsf (100 kPa). Consequently, the method of saturating the inner barrel was believed to be adequate.

<u>Constant temperature water bath</u>. Based upon the difficulty of calibrating the WES psychrometer, a decision was made to construct a controlled temperature water bath to house the triaxial devices. It was believed this bath would minimize potential testing errors which

could result from laboratory temperature fluctuations. An acrylic tank was designed and fabricated which allowed the triaxial devices to be submerged in water. The water was continuously circulated as each test or calibration was conducted. A constant temperature of 25.00 $\pm$ 0.02 deg C was maintained by the operation of a three kilowatt heater which was controlled by a thermistor. To ensure thermal equilibrium between the water in the tank and the soil specimen in the triaxial apparatus, the assembled device was allowed to thermally equilibrate overnight before a test or calibration was initiated. The time required to achieve equilibrium was estimated to be six to eight hours based upon data published by Hodgman, Weast and Selby (1961).

Diffusion of air and water through the latex membrane. Poulos (1964) conducted an investigation of leaks in the triaxial test. He indicated that a major error was caused by the diffusion of air and water through the membrane enclosing the soil specimen. For tests on back pressure saturated specimens, this problem is usually ignored because the gradient across the membrane is generally small, i.e. limited to a few tsf or a few hundred kPa. However, for tests on unsaturated soils, very large gradients which consisted of the applied stress plus soil suction could exist across the membrane. These large gradients would tend to cause water or air to diffuse through the membrane. As air or water diffused through the membrane, the specimen conditions could change as the test was being conducted. To minimize the potential for this problem, a method was needed to minimize the diffusion of air and water through the membrane.

To assess the problem, four conditions were studied. The first case, which provided a reference condition for evaluating the effectiveness of a particular leak prevention measure, consisted of wrapping an aluminum cylinder with filter paper and enclosing the configuration within a latex membrane. The second case consisted of covering the aluminum cylinder, filter paper and latex membrane configuration described above with a thin film of silicon grease and another latex membrane. For the third case, a thin film of silicon grease, plastic wrap and latex membrane were placed over the aluminum cylinder, filter paper

and latex membrane configuration described as case 1. The fourth condition was identical to case 3 except aluminum foil was substituted for the plastic wrap.

To check for diffusion of air through the various membrane configurations, an air pressure difference of 1 tsf (96 kPa) was applied across the membrane. A pressure transducer was used to measure the rate of change of air pressure in the cavity formed by the filter paper and the pore pressure system on the triaxial apparatus. The rate of change of air pressure in the pore pressure cavity decreased from approximately 0.3 tsf/hr (30 kPa/hr) for a single latex membrane configuration to less than 0.01 tsf/hr (1 kPa/hr) for the configuration using overlapping aluminum foil squares placed between two membranes. The rates of diffusion of air through the membrane configurations identified as cases 2 and 3 were 0.1 tsf/hr (10 kPa/hr) and 0.03 tsf/hr (3 kPa/hr), respectively.

To check the rate of diffusion of water across the membrane, the filter paper configurations described as cases 1 through 4 were back pressure saturated and consolidated by an effective stress of approximately 12 tsf (1150 kPa). The volume of water expelled from the saturated filter paper system as a function of time was recorded. For the single membrane condition identified as case 1, a "leak", which was indicated by a change of the slope of the burette reading versus the logarithmic time relationship, occurred after 1 hour. For case 4, there was no indication of a leak after one week, which was the time required to test an unsaturated soil specimen.

To assess the effects of the membranes and aluminum foil on the geotechnical properties of soil specimens, a latex cylinder was substituted for the aluminum cylinder described for conditions 1 through 4 and a shearing load was applied to the cylinder. It was determined that Young's modulus was not significantly different for any of the four conditions. Based upon these observations, it was concluded that a grid of overlapping aluminum foil squares could be used to minimize the diffusion of air and water across the triaxial membranes without adversely affecting the test results.

Testing Procedures

Specimen Preparation Procedures

Preparation of Vicksburg buckshot clay for testing consisted of air drying and pulverizing the material until all soil passed the No. 10 (2 mm.) U.S. standard sieve. The soil was thoroughly mixed to ensure uniformity and was then stored in a drum until it was needed for testing.

Prior to compacting each specimen, air dried soil was placed in a mixing bowl with a sufficient quantity of distilled water to increase the water content of the moist soil to approximately 21 or 27 percent and thoroughly mixed with an electric mixer. After mixing, the moist soil was forced through a 1/4 inch hardware cloth (5.7 mm. openings), placed in a plastic container and sealed to allow the moisture in the soil to equilibrate. Three or four days later, the moist soil was remixed to ensure a uniform water content. A mellowing time of one week was allowed before the soil was compacted.

A similar procedure was used for preparing specimens of buckshot clay which were treated with KCl prior to testing. The only variation of the routine used for treated specimens as compared to untreated specimens was that potassium chloride was added to distilled water prior to mixing with the soil. For each specimen, the weight of KCl was adjusted as required to maintain a selected value of solute suction, regardless of the water content of the specimen.

All specimens were compacted into a 2.8 in. (7.1 cm.) diameter by 6.0 in. (15.2 cm.) high mold using the kneading compactor which is illustrated in Figure 13. Two compactive efforts were used. Most of the specimens were compacted using a "low" compactive effort. The low effort compaction curve was established by a trial and error procedure of adjusting the water content of the soil, the tamping foot pressure, the number of tamps, and the number of layers or lifts until the density of the compacted specimen at its optimum water content was similar to the density of specimens compacted using standard impact compaction

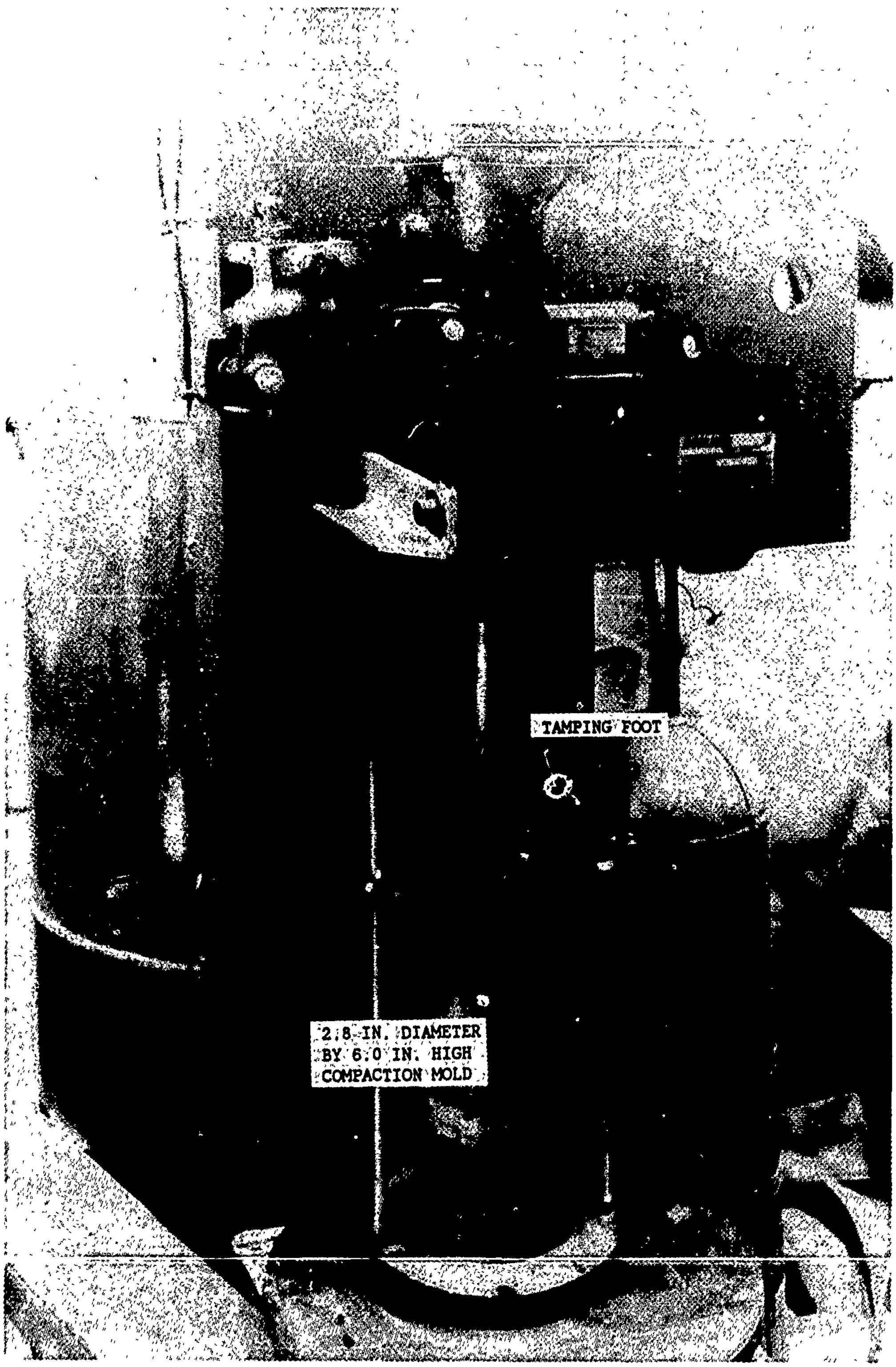

FIG. 13. Kneading compaction apparatus with mold for specimens 2.8 in. (7.1 cm.) diameter by 6.0 in. (15.2 cm.) high.

(Brabston, 1981; Horz, 1983). After the compaction procedures were established, specimens were compacted at water contents ranging from 12 to 32 percent.

For the low compactive effort, 9 tamps were placed on each 1/2 in. (1.3 cm.) thick lift by a 1.3 in. (3.3 cm.) diameter compaction foot. Care was taken to ensure the surface area of the soil in the mold was completely covered by the action of the tamping foot. The material was scarified between lifts to minimize planes of weakness. Thirteen lifts were required to build the specimen to a height slightly in excess of 6.0 in. (15.2 cm). After compaction, the collar was removed and the specimen was trimmed to the top of the mold. The specimen was then removed from the mold, covered with a plastic wrap, coated with wax and placed in a humid room. On the following morning, the specimen was prepared for testing.

Similar procedures were developed for compacting specimens using the "high" compactive effort. For the high compactive effort, the only significant change in procedures as compared to the procedures used for compacting specimens by the low compactive effort was that the tamping foot pressure was increased.

Compaction of Buckshot Clay

The kneading compaction characteristics of Vicksburg buckshot clay are presented in Figure 14. Compaction data are tabulated in Appendix II. The optimum water content for the low effort compaction curve was 23.2 percent with a corresponding density of 99.3 lb/ft^3 (1590 kg/m^3). The optimum water content for the high effort compaction curve was 19.7 percent with a corresponding density of 105.1 lb/ft^3 (1680 kg/m^3). As may be observed from impact compaction data (Brabston, 1981; Horz, 1983) which have been superimposed in Figure 14, the low effort and high effort compaction characteristics of buckshot clay obtained by kneading compaction are similar to the compaction curves obtained by impact compaction using compactive efforts of approximately 12,000 ft-lb/ft^3 (5.8 MJ/m^3) and 26,000 ft-lb/ft^3 (12.5 MJ/m^3), respectively.

The compaction curves for buckshot clay which had been treated with potassium chloride were also developed. The compaction procedures

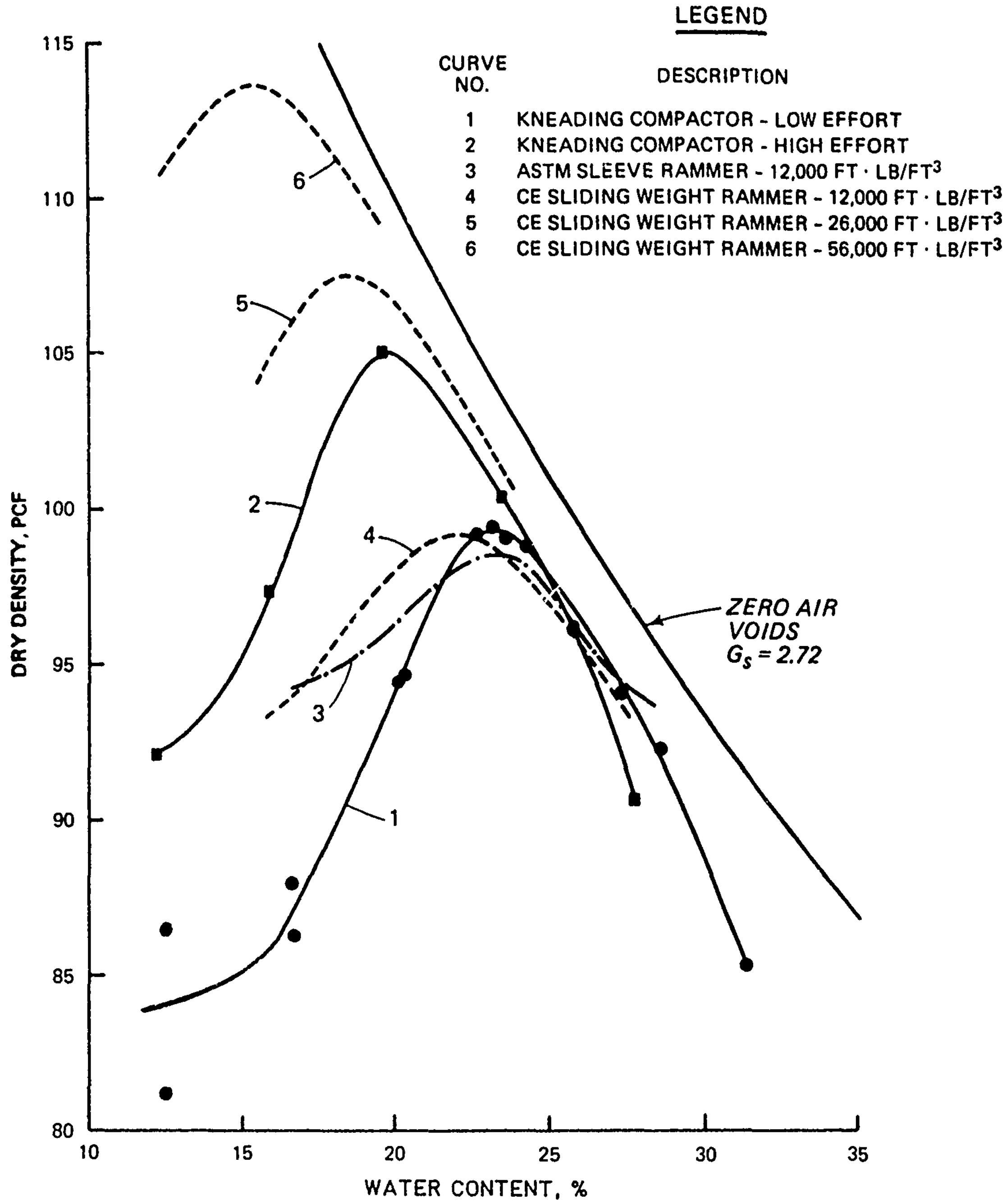

FIG. 14. Compaction relationships for Vicksburg buckshot clay obtained by kneading compaction for this investigation and by impact compaction using the American Society for Testing and Materials (ASTM) sleeve rammer (After Horz, 1983) and the Corps of Engineers (CE) sliding weight rammer (After Brabston, 1981). (1000 ft-lb/ft^3 = 480 kJ/m^3; 100 lb/ft^3 = 1600 kg/m^3)

were identical to the procedures used for low effort compaction of untreated specimens. Five different concentrations of KCl were used. Nominal values of solute suction were 0.8, 1.1, 3, 5 and 18 tsf (0.08, 0.11, 0.3, 0.5 and 1.7 MPa). The compaction data for the treated specimens have been presented with the low effort compaction data for untreated specimens in Figure 15. The compaction data for these specimens are also tabulated in Appendix II. For each specimen, the weight of salt was adjusted as the compaction water content was changed to maintain a value of solute or osmotic suction which was nearly constant for each compaction curve. From these data, one may observe that the treatment of buckshot clay with KCl did not significantly affect the compaction characteristics of the soil.

Void Ratio-Suction Tests

Prior to selecting a device to measure suction, a few preliminary tests were conducted on specimens of buckshot clay to determine a range of suction stresses. The apparatus which was used for these preliminary suction tests consisted of a psychrometer, a container for the soil specimen and a microvoltmeter to measure emf (Johnson, 1974a, 1974b). To conduct a test, a lump of soil and a psychrometer were sealed in a container. After the relative humidity of the soil had equilibrated with the air in the container, suction measurements were made. A photograph of the apparatus is presented in Figure 16. A container for the soil specimen and a rubber stopper which is used to seal the container are located in the lower right of the photograph. Note that a psychrometer has been inserted through the rubber stopper. The microvoltmeter is shown in the lower left quadrant of the photo. An ammeter, which is used to measure the electrical current applied to the psychrometer, is located in front of the voltmeter. A switching panel for testing as many as 24 specimens is located above the voltmeter. Before a test is conducted, the container of soil is placed in the insulated chest, which is shown in the upper right quadrant of the photo, and allowed to equilibrate for approximately 48 hours.

Results of suction tests on moist soil specimens are expressed in Figure 17 as total suction (logarithmic scale) versus water content.

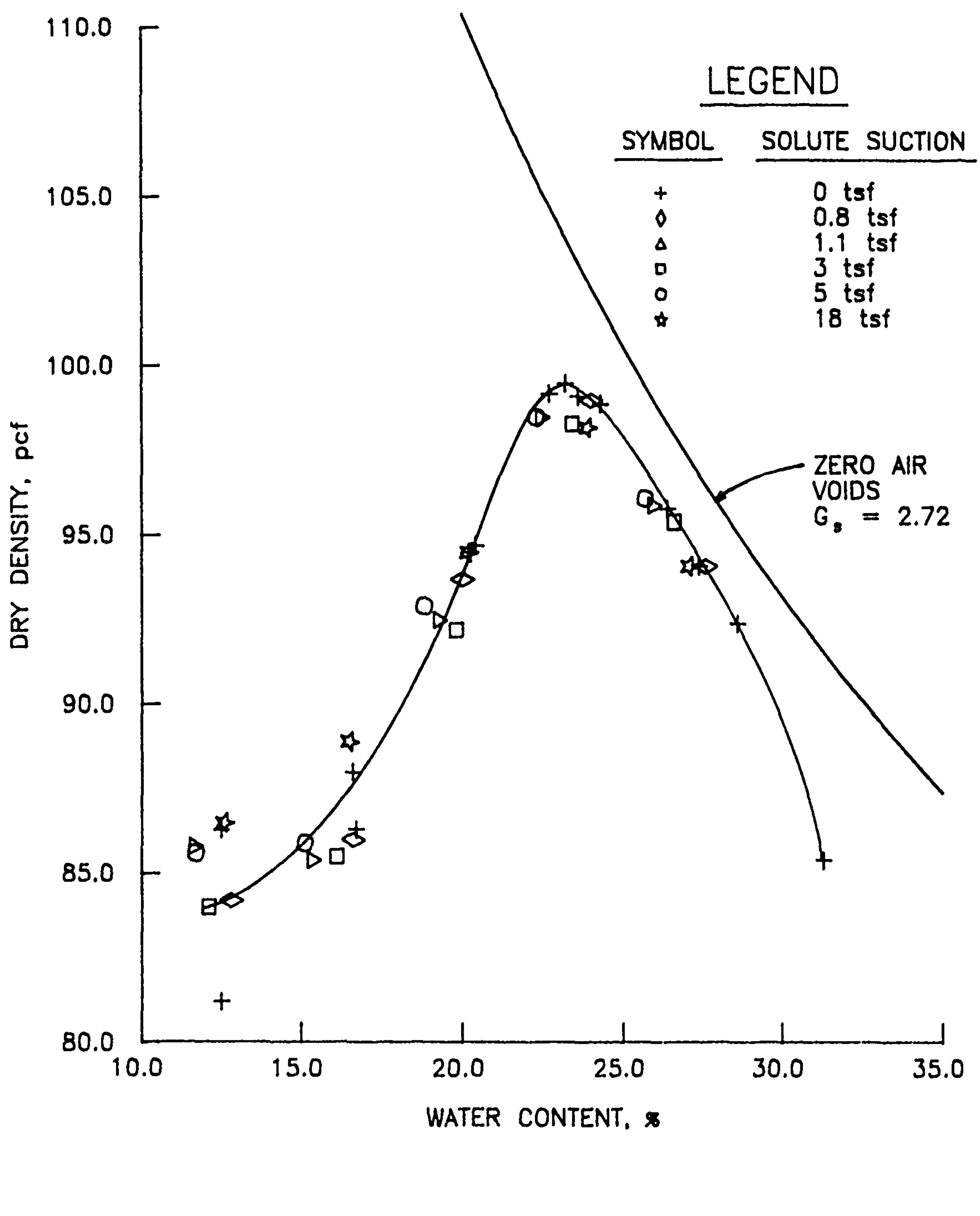

FIG. 15. Compaction characteristics of Vicksburg buckshot clay treated with potassium chloride. (1 tsf = 96 kPa; 100 lb/ft^3 = 1600 kg/m^3)

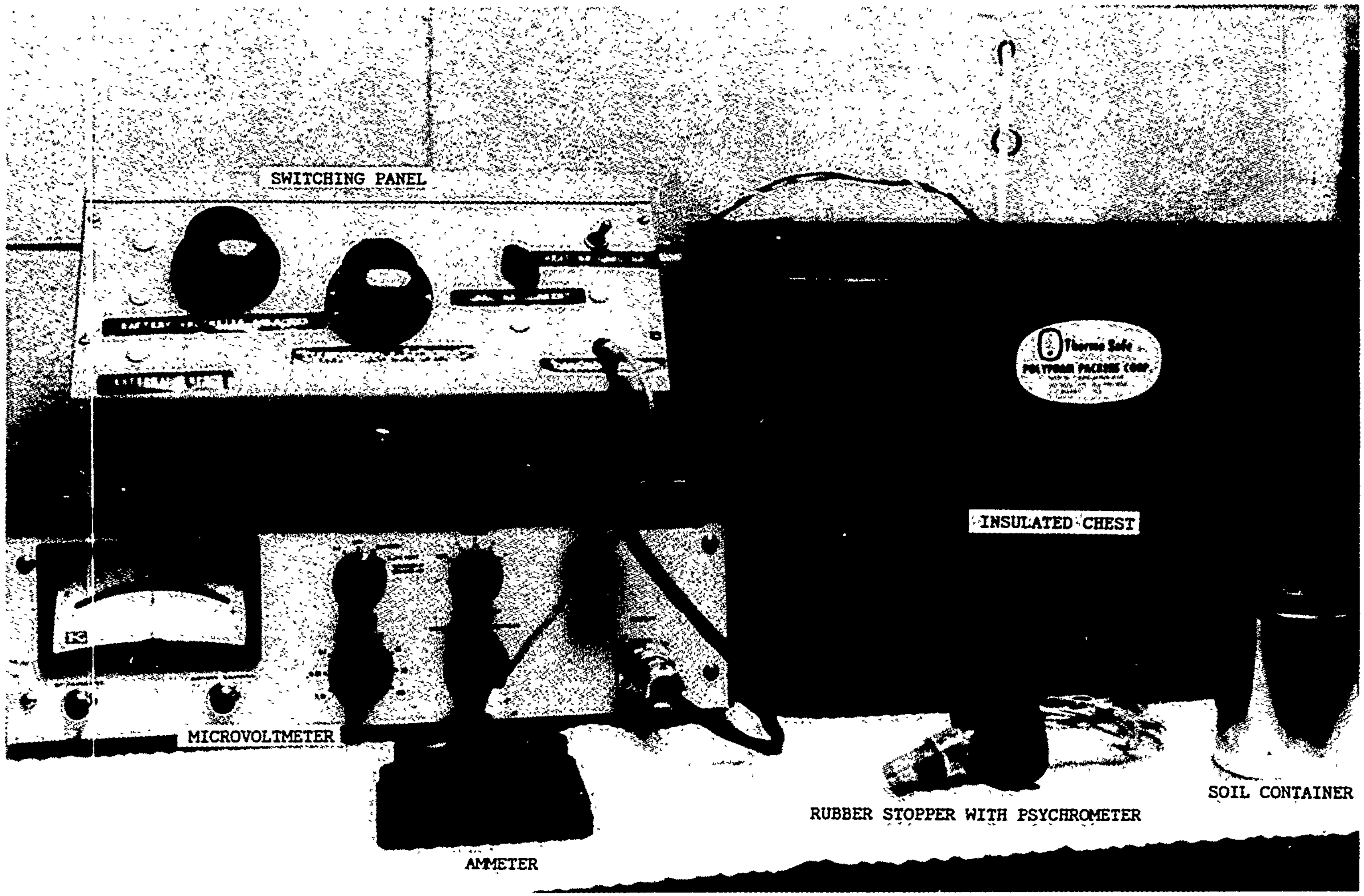

FIG. 10. Psychrometers inserted into triaxial specimen for measurement of total suction (After Johnson, 1974a).

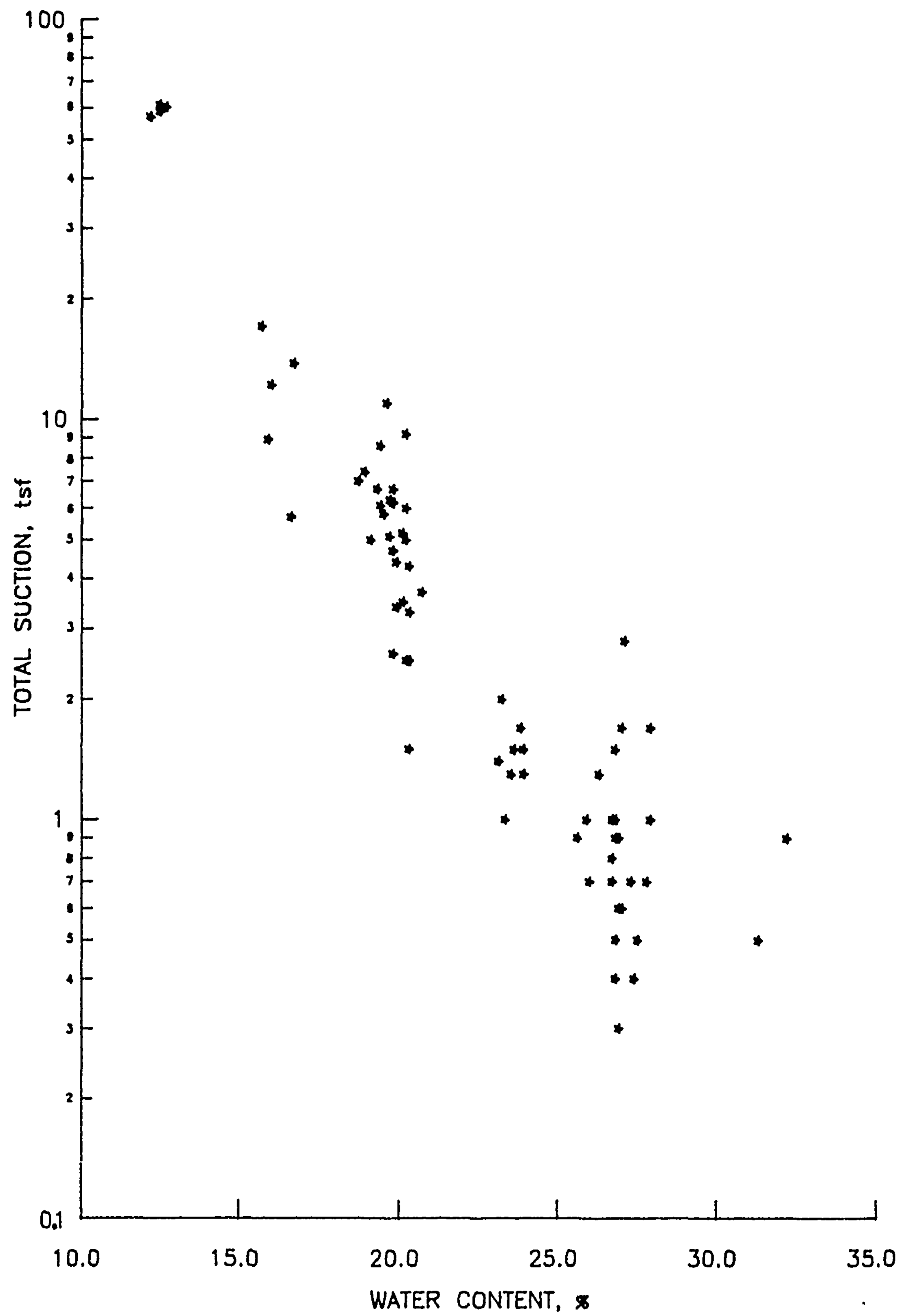

FIG. 17. Total suction versus water content for compacted specimens of buckshot clay. (1 tsf = 96 kPa)

Data are also summarized in Appendix III. As can be seen from the data in Figure 17, suction ranged from less than 1 tsf (100 kPa) for specimens at a water content of 27 percent to greater than 60 tsf (5.8 MPa) for specimens at a water content of 12 percent. Although there is much scatter in the data, it is obvious that suction increased as the water content of the specimens decreased, which is consistent with the suction versus water content relationships reported by others. Total suction versus void ratio relationships for these specimens were also examined. Unfortunately, a relationship of suction versus void ratio was not found. For each of these tests, the specimens were allowed to equilibrate in the soil containers for approximately 48 hours before suction was measured. When the tests were conducted, a cooling current of 8 milliamps was applied to the psychrometer for 15 seconds. After the cooling current was terminated and the voltmeter had stabilized, the maximum value of emf was recorded.

One Dimensional Consolidation Tests

One dimensional consolidation tests were used to develop an equivalent consolidation pressure, P_e, which was required to normalize the effects of density variation between individual triaxial test specimens. From each soil specimen which had been compacted at nominal water content of 21 or 27 percent, three specimens with nominal dimensions of 2.5 in. (6.3 cm.) diameter by 1.25 in. (3.2 cm.) high were prepared for consolidation testing. After the initial specimen conditions were recorded, each specimen was placed in a consolidometer. Moist paper towels were placed in the inundation ring of each consolidometer, the devices were covered with aluminum foil or a rubber membrane and a nominal seating load of 0.125 tsf (12.0 kPa) was applied to each specimen; the seating load was allowed to remain on the specimens overnight before the consolidation tests were initiated. The moist paper towels were placed in the inundation rings of each consolidometer to help minimize the drying of the soil specimens before the tests were initiated.

Before the consolidation tests were conducted, the aluminum foil and paper towels were removed from two consolidometers. The specimens

were inundated and subjected to initial conditions dictated by the swell and swell pressure tests, which are described in Engineer Manual EM 1110-2-1906 (Department of the Army, Office of the Chief of Engineers, 1970) and American Society for Testing and Materials (1989) Standard D-4546. To conduct the swell test, the specimen was inundated and permitted to swell against a constant pressure prior to initiating the consolidation test. To conduct the swell pressure test, the surcharge load was adjusted as required to maintain a constant specimen volume after the specimen was inundated. After the swell and swell pressure tests were completed, the specimens were consolidated.

The third specimen was consolidated at the "as compacted" or natural water content condition. For this specimen, the rubber membrane which covered the inundation ring was not removed during the test. Periodically, however, the membrane was opened and a few drops of water were added to the moist paper towels.

The loading sequence for each specimen consisted of the application of a stress or load increment for 24 hours. After each specimen had consolidated for 24 hours, the load was doubled and the specimen was permitted to equilibrate under the larger stress for an additional 24 hours. This process was repeated until the loading sequence was completed. Generally, the maximum value of applied stress was 128 tsf (12.3 MPa), although some tests were rebounded at lower stresses if soil was extruded around the top loading platen. During the unloading sequence, the specimen was allowed to equilibrate against a particular stress for 24 hours. The first rebound stress was usually one half of the maximum consolidation stress. Each succeeding stress increment was decreased to one fourth of the previously applied stress until a nominal seating load of 0.125 tsf (12.0 kPa) remained on the specimen. Rebound-reload cycles were conducted on most specimens at applied stresses of 4 and 16 tsf (0.4 and 1.5 MPa). Results of the consolidation tests are discussed in the section entitled "Test Results and Analysis of Data". Consolidation data for each specimen are tabulated in Appendix IV.

Fixed ring consolidometers, similar to the devices described in Engineer Manual EM 1110-2-1906 (Department of the Army, Office of the

Chief of Engineers, 1970), were used. The load or consolidation stress was applied using a balanced beam loading frame with a mechanical advantage of 40:1. Dial gages graduated to 0.0001 in. (0.0025 mm.) were used to measure the deformation of the soil specimens. Total suction was measured during consolidation of unsaturated specimens by a psychrometer which had been inserted into the top loading platen of the consolidometer. However, these suction measurements were suspect because filter paper was placed across the screen on the psychrometer housing to prevent soil from entering the housing during the test. The filter paper may have caused a lag time between the measured and actual values of suction.

A photograph of the top loading platen which was modified to house the psychrometer is shown on the right side of Figure 18. A coarse porous stone and a brass disk are shown in the center of the photograph. These spacers were placed between the soil specimen and the top platen. After each specimen was compacted, it was trimmed into a confining ring, as shown on the left side of the photograph, and then placed in the consolidometer for testing. Suction was measured using the microvoltmeter which is shown in Figure 17. A cooling current of 8 milliamps was applied to the psychrometer for 15 seconds. Following the application of the cooling current, the emf was recorded as soon as the voltmeter had stabilized.

Triaxial Tests on Saturated Specimens

To provide a reference strength to evaluate the influence of suction on the shear strengths of unsaturated soil, triaxial tests were conducted on 1.4 in. (3.6 cm.) diameter by 3.0 in. (7.6 cm.) high back pressure saturated specimens. After the initial conditions of each specimen were obtained, the specimen was placed on the base platen of the triaxial apparatus and wrapped with a filter paper cage and two latex membranes. After the test device was assembled, a vacuum of 1 tsf (100 kPa) was applied to the specimen and allowed to remain on the specimen overnight.

During the following day, deaired water which contained less than 2 parts per million (ppm) dissolved oxygen was allowed to seep into the

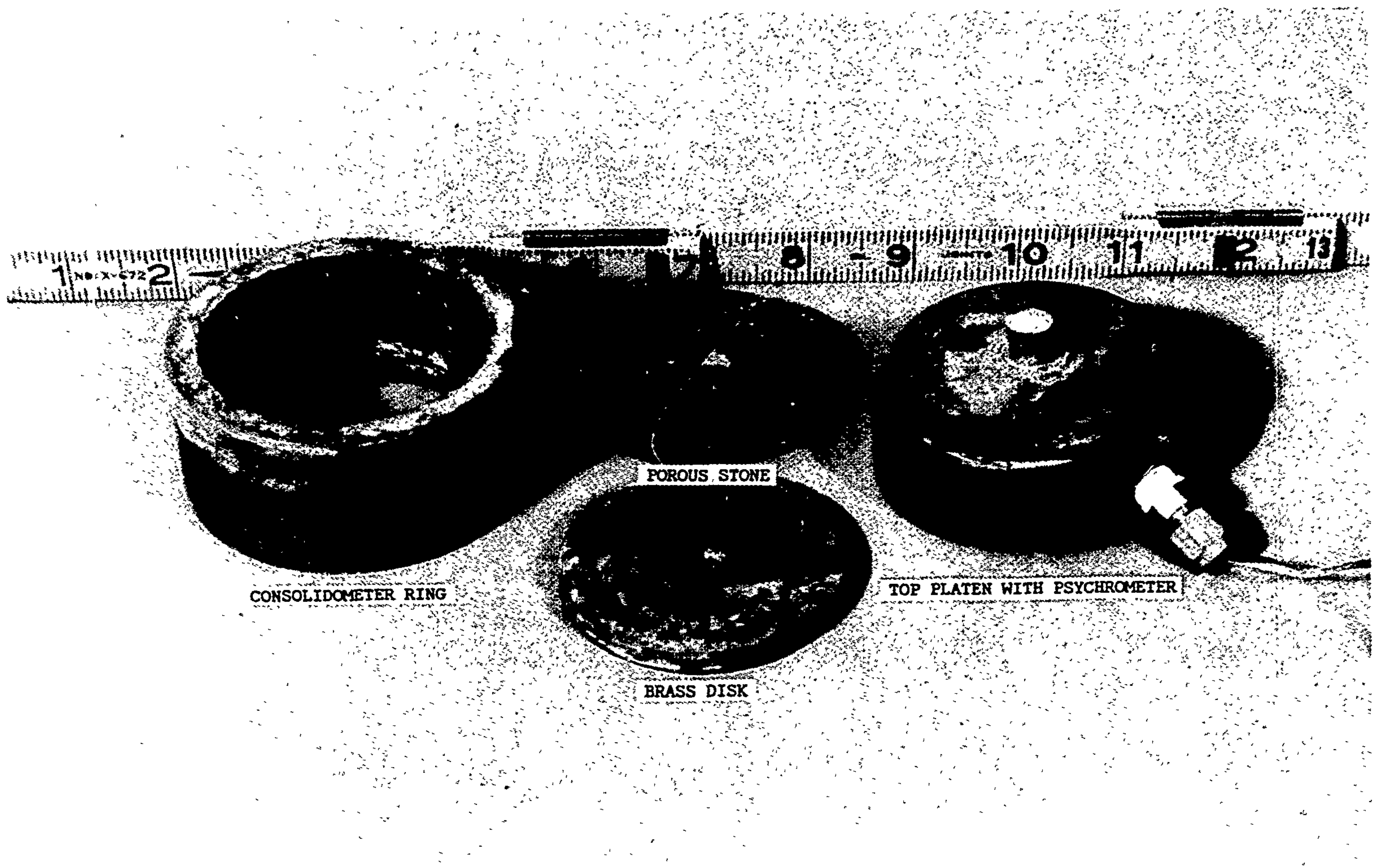

FIG. 18. Load platen of fixed ring consolidometer which was modified to measure total suction during consolidation tests on unsaturated specimens.

soil specimen. When a volume of water which was approximately 50 percent greater than the volume of the voids for a particular specimen had seeped through the specimen, the vacuum was slowly reduced to atmospheric pressure and the chamber pressure was simultaneously increased to approximately 0.3 tsf (30 kPa). Specimens were then allowed to free swell for approximately 24 hours.

On the third day, back pressure was applied to the specimen to ensure saturation, i.e. B greater than 0.95. As the back pressure was increased, the chamber pressure was adjusted to maintain an effective stress of approximately 0.3 tsf (30 kPa) on the test specimen. Following back pressure saturation, specimens were consolidated by an isotropic stress of 2.9 or 11.5 tsf (0.3 or 1.1 MPa) prior to rebound and/or shear. Rebound stresses were 5.8, 2.9, 1.4, 0.7 or 0.35 tsf (550, 280, 140, 70 or 35 kPa). Consolidation or rebound stresses were applied in one loading or unloading increment. Although primary consolidation or rebound occurred in less than 8 hours, each specimen was allowed to equilibrate overnight before testing was continued.

Consolidated undrained triaxial tests with pore pressure measurements were conducted on the back pressure saturated specimens. The specimens were sheared in 24 hours using a rate of strain of 0.8 percent/hour. During the shear phase, continuous records of axial load, axial deformation, pore water pressure and chamber pressure were obtained with a strip chart recorder. Pore water pressures and chamber pressures were recorded to the nearest 0.01 tsf (1 kPa) using electronic pressure transducers. Axial loads were recorded to the nearest 0.1 lb (0.45 N) using an electronic load cell. Axial deformations were recorded to the nearest 0.001 in. (0.025 mm.) using an LVDT (linear variable differential transformer). Test results are discussed in the section entitled "Test Results and Analysis of Data." Test data are presented in Appendix V.

Triaxial Tests on Unsaturated Specimens

The procedures for conducting triaxial tests on unsaturated specimens were slightly different than the procedures used for tests on saturated specimens. After the initial specimen conditions were obtained,

a hole, 0.35 in. (0.9 cm.) diameter by 1.3 in. (3.3 cm.) long, was carefully drilled into the center of and perpendicular to one end of a 2.8 in. (7.1 cm.) diameter by 6.0 in. (15.2 cm.) high compacted specimen. As the specimen was placed on the base platen of the triaxial apparatus, the housing for the psychrometer was carefully inserted into the hole in the specimen. Before the triaxial apparatus was assembled, the specimen was covered with overlapping strips of filter paper, a latex membrane, silicone grease, an overlapping grid of aluminum foil squares and finally another latex membrane.

After the apparatus was assembled, small vacuums were applied to the specimen and to the double barrel triaxial chamber. These vacuums were subsequently increased until pressures of -1.0 tsf (-100 kPa) and -0.8 tsf (-80 kPa) had been applied to the specimen and to the chamber, respectively. Approximately 2 hours elapsed before the double barrel chamber was filled with deaired water. After the chamber had been filled with water, the pressures to the specimen and to the chamber were simultaneously increased. When the pore air pressure was zero (atmospheric pressure) and the chamber pressure was 0.2 tsf (20 kPa), the triaxial device was placed in the tank used as the water bath. The tank was filled with water which was subsequently heated to 25 deg C. To ensure thermal equilibrium within the triaxial apparatus and the unsaturated soil specimen, the system was allowed to equilibrate overnight before a test was initiated. Throughout this procedure, a differential pressure of 0.2 tsf (20 kPa) was carefully maintained between the chamber and the specimen.

On the following morning, consolidation of the unsaturated specimen was initiated. All specimens were isotropically consolidated by stresses of 0.7, 1.4, 2.9, 5.8 or 11.5 tsf (70, 140, 280, 550 or 1100 kPa). Selected specimens were then rebounded from 2.9 or 11.5 tsf (0.3 or 1.1 MPa) to isotropic stresses of 5.8, 2.9, 1.4 or 0.7 tsf (550, 280, 140 or 70 kPa). Consolidation or rebound stresses were applied in one loading or unloading increment. Although most of the deformation or swell of the unsaturated specimens occurred within a few minutes following a change of stress, specimens were allowed to equilibrate under the applied stresses for 48 hours before testing was continued.

Specimens were sheared using a controlled loading method with about 12 load increments to failure. To determine the magnitude of each load increment, the failure load for each specimen was estimated and divided by 12. Each load increment was applied to the specimen for 4 hours before test data, i.e. load, chamber pressure, axial deformation, volume change, suction and time, were recorded. After these data were obtained, the load was increased to the next increment. This procedure was repeated until the specimen had failed.

The rates for testing unsaturated specimens were arbitrarily selected as little information was available in the literature. The selection of 48 hours for consolidation was based upon Bishop's guidance for testing unsaturated soils (Bishop, Blight and Donald, 1961) and the consolidation data obtained from tests on saturated specimens reported herein. Bishop and his colleagues suggested the length of time for testing unsaturated specimens should be increased "by a factor of two for soils not close to a degree of saturation of 100%" as compared to the rates for testing saturated specimens. The time required to consolidate or rebound a saturated specimen 1.4 in. (3.6 cm.) diameter by 3.0 in. (7.6 cm.) high ranged from 1 to 8 hours. Using these test results, the time required to consolidate or rebound a saturated specimen 2.8 in. (7.1 cm.) diameter by 6.0 in. (15.2 cm.) high was estimated as 4 to 32 hours. Following Bishop's recommendation that the time for testing unsaturated soils should be multiplied by two as compared to the time required for testing saturated soils, it was concluded that unsaturated specimens should equilibrate 1 to 3 days after the application of consolidation or rebound stresses before testing was continued.

Unsaturated specimens were sheared in 48 hours. This period of time was selected after consideration was given to the consolidation data obtained from saturated specimens, the American Society for Testing and Materials (1989) procedure for conducting consolidated undrained triaxial tests with pore pressure measurements (ASTM Standard D 4767) and Bishop's recommendation of rates for testing unsaturated soils. Based upon the ASTM procedure, the rate of strain for shearing a saturated specimen may be estimated "by dividing 4% by 10 times the value of t_{50}", where t_{50} is the time required for 50 percent of primary

consolidation to occur. For the study reported herein, t_{50} for specimens 1.4 in. (3.6 cm.) diameter by 3.0 in. (7.6 cm.) high ranged from a few minutes to 1 hour. Considering the differences of sizes for specimens, the estimated value of t_{50} for specimens 2.8 in. (7.1 cm.) diameter by 6.0 in. (15.2 cm.) high was 1 to 4 hours; the time required for shearing these specimens to 15 percent axial strain would be approximately 38 to 150 hours. Following Bishop's criteria that the elapsed time for testing unsaturated soils should be two times longer than the time required for testing saturated soils, the time required for shearing unsaturated specimens was of the order of 3 days to 2 weeks per specimen. Unfortunately, this period of time would not permit the investigation to be completed in a timely manner. Therefore, 48 hours, which was the length of time selected for consolidation and rebound of unsaturated specimens, was arbitrarily selected as the length of time to shear the unsaturated specimens.

The axial loading system was automated by an analog timing device. When the timing device was activated, a solenoid valve was opened which permitted an increase of air pressure to a diaphragm air cylinder used to apply axial load to the test specimen. After the load had been applied for 3 hours 50 minutes, a cooling current was applied to the thermocouple psychrometer for 9 minutes 30 seconds. When 9 minutes 30 seconds had elapsed, the cooling current was terminated. After an additional 30 seconds had elapsed, all channels of data were scanned and recorded. The timing device was then automatically reset and another solenoid valve was opened which increased the pressure to the air cylinder. This process was repeated until each specimen was failed.

The decision to use 9 minutes 30 seconds for application of the cooling current to the psychrometer followed by a 30 second delay before the test data were automatically recorded was based upon observations during the calibration of several psychrometers. It was noted that a variation of a few seconds for the length of time in which the cooling current was applied to the psychrometer did not adversely affect the measured values of emf. The 30 second delay following the

termination of the current to the psychrometer appeared to be an optimum length of time in which the voltmeter had stabilized and repeatable values of emf could be recorded.

Axial load, axial deformation, chamber pressure, volume change and suction measurements were recorded automatically using a digital voltmeter and printer, although manual readings could be obtained as required. Axial deformations were recorded to the nearest 0.001 in. (0.025 mm.) using an LVDT. Axial loads were recorded to the nearest 0.1 lb (0.45 N) and the chamber pressure was recorded to the nearest 0.01 tsf (1 kPa) using an electronic load cell and a pressure transducer, respectively. The volume change measurements were made by a differential pressure transducer which was plumbed to a 0.5 in. (1.3 cm.) diameter burette. The differential pressures caused by the head of water in the burette were recorded to the nearest 0.0001 tsf (0.01 kPa). A pressure change of 0.0001 tsf (0.01 kPa) corresponded to a change of volume of the soil specimen of 0.05 ml or a change of void ratio of approximately 0.0001. The emf of the psychrometer was recorded to the nearest 0.1 μvolt, which is equivalent to a value of suction of approximately 0.2 tsf (20 kPa). Again, the reader is reminded that suction measurements are suspect because filter paper was placed across the screen on the tip of the psychrometer housing to prevent soil from entering the housing during the triaxial test. Filter paper could cause a lag time between the actual values and the measured values of suction. Triaxial test results on unsaturated specimens are discussed in the section entitled "Test Results and Analysis of Data." Test data are presented in Appendices VI and VII for unsaturated specimens of buckshot clay and unsaturated specimens of buckshot clay treated with potassium chloride, respectively.

Figure 19 is a photograph of a compacted specimen of buckshot clay. Behind the specimen is the split mold used for compacting specimens. The template which served as a guide for drilling a hole into one end of the specimen for placement of the psychrometer housing is shown in the lower left quadrant of the photo. One may observe that a hole has been drilled into the specimen shown in the photograph.

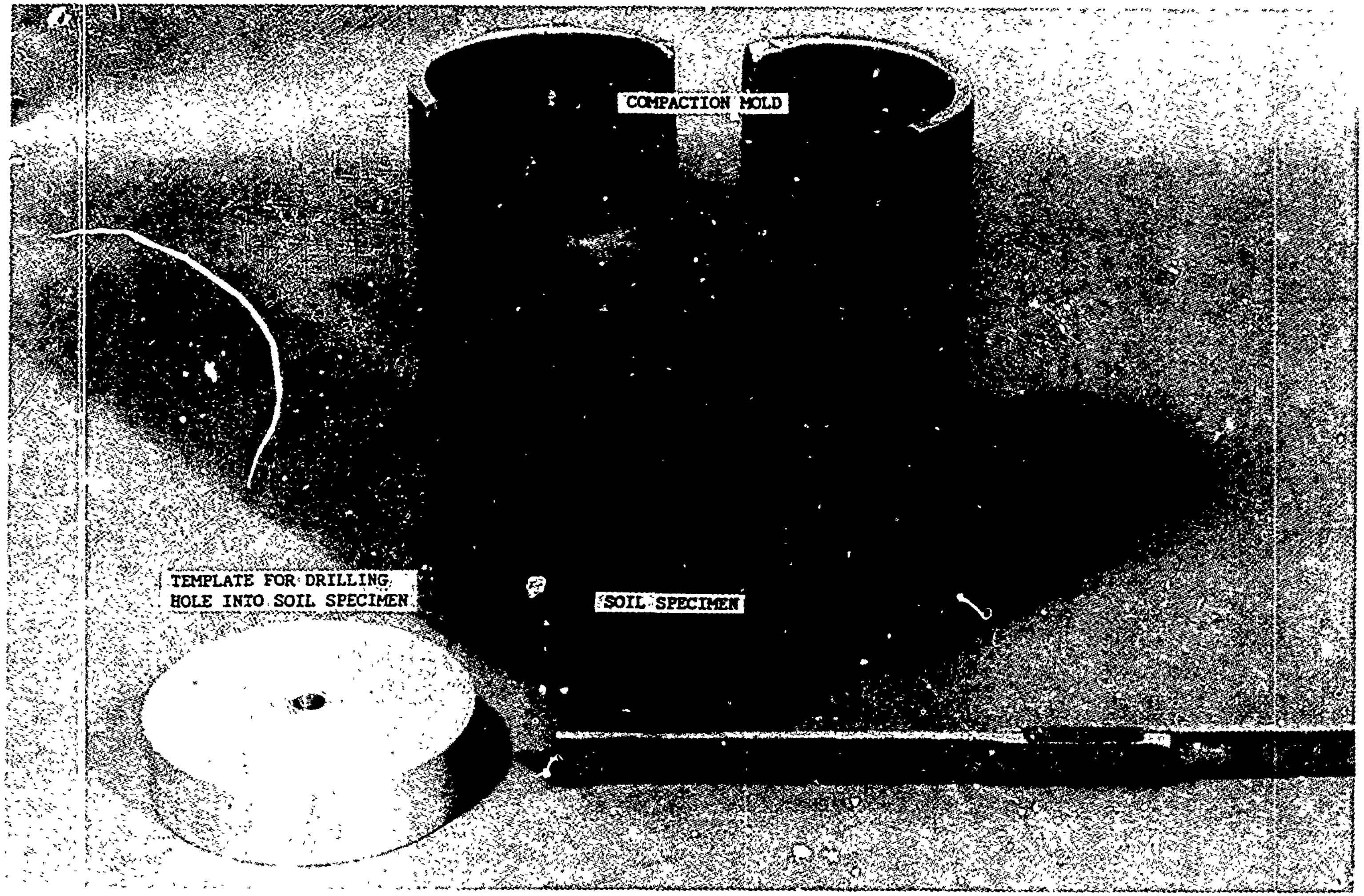

FIG. 19. Compacted specimen of buckshot clay.

Figure 20 is a photograph of the psychrometer housing. The large end of the housing, located near the center of the photograph, was placed in a recessed hole in the triaxial base platen. The small piece located on the right side of the photograph is the cover for the psychrometer housing. A fine wire mesh was attached to one end of the cover which allowed the measurement of suction within the soil specimen. This cover was used to exclude soil from the psychrometer housing during the test. During the test, a small piece of filter paper was placed over the screen to prevent soil from entering the housing and damaging the psychrometer.

Figures 21 through 28 illustrate the procedures used to prepare triaxial specimens for testing. Figure 21 is a photograph of the base of the triaxial chamber. The psychrometer has been inserted through the base platen. In Figure 22, the housing has been placed over the psychrometer and the porous stone has been placed on the base platen. Figures 23 and 24 illustrate the placement of the filter paper cage and aluminum foil grid on a soil specimen. The inner chamber barrel used for determining volume change in unsaturated specimens can be seen in Figures 25 and 26. Figure 25 illustrates the relative size of the specimen and the inner chamber while Figure 26 shows the inner chamber within the frame of the triaxial device. Figure 27 is a photograph of the assembled triaxial device. Figure 28 shows two triaxial devices setting in the water tank. The burette panel is shown in the center of this photograph. Two burettes were attached to each triaxial device to measure the volume of water expelled from the inner chamber during each test.

Figure 29 is a photograph of the instrumentation rack used for controlling the loading sequence to unsaturated specimens and for recording the test data. A digital printer is located at the top of the rack. Signal conditioning units are located in the middle section of the instrumentation rack. Pressure regulators which were used to supply air pressure to the diaphragm air cylinders for shearing the triaxial specimens are located in the lower portion of the photograph. The analog timing device which was used to control the test operations is located at the bottom of the figure.

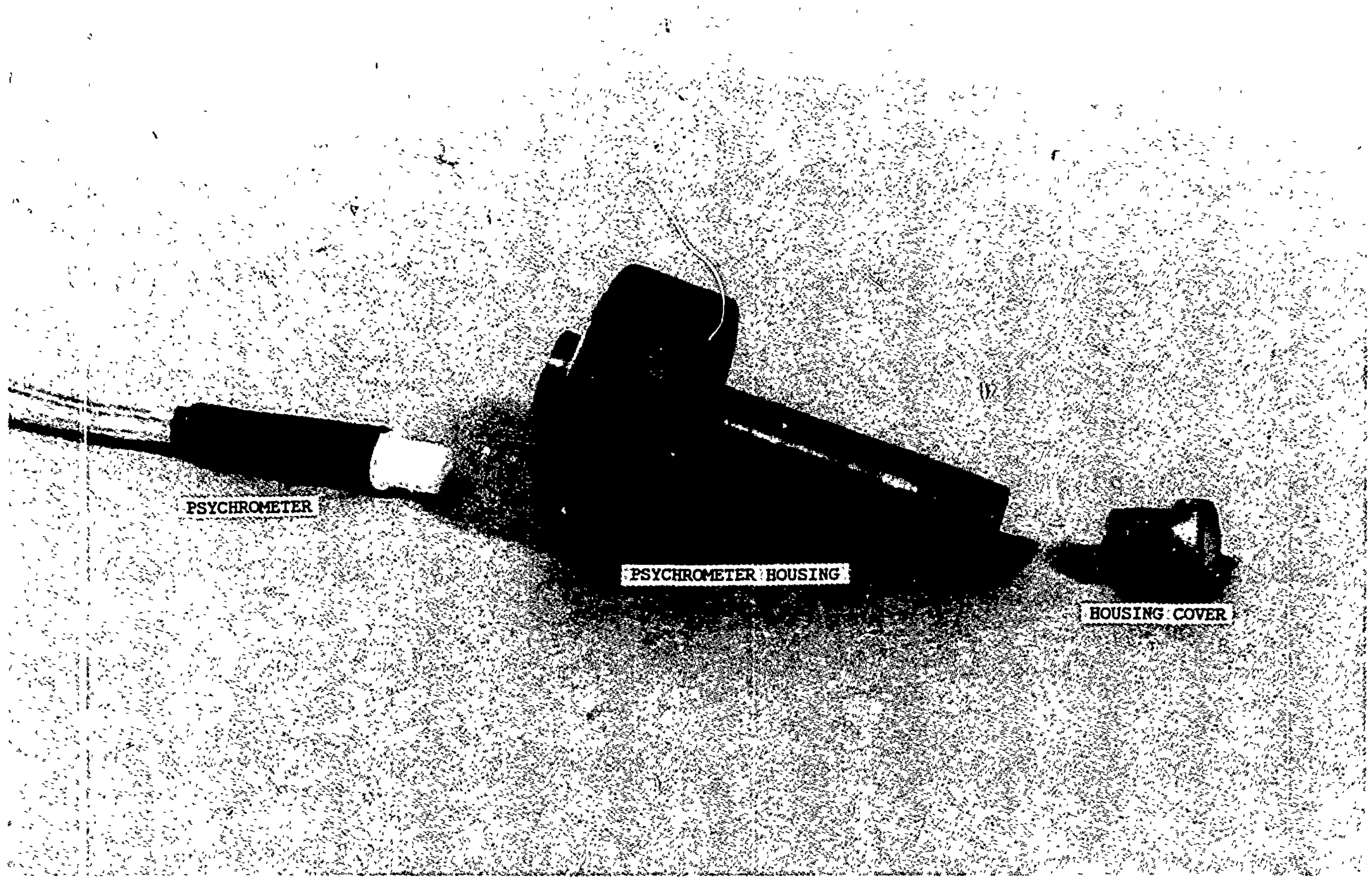

FIG. 20. Thermocouple psychrometer with special housing for testing unsaturated specimens in triaxial compression.

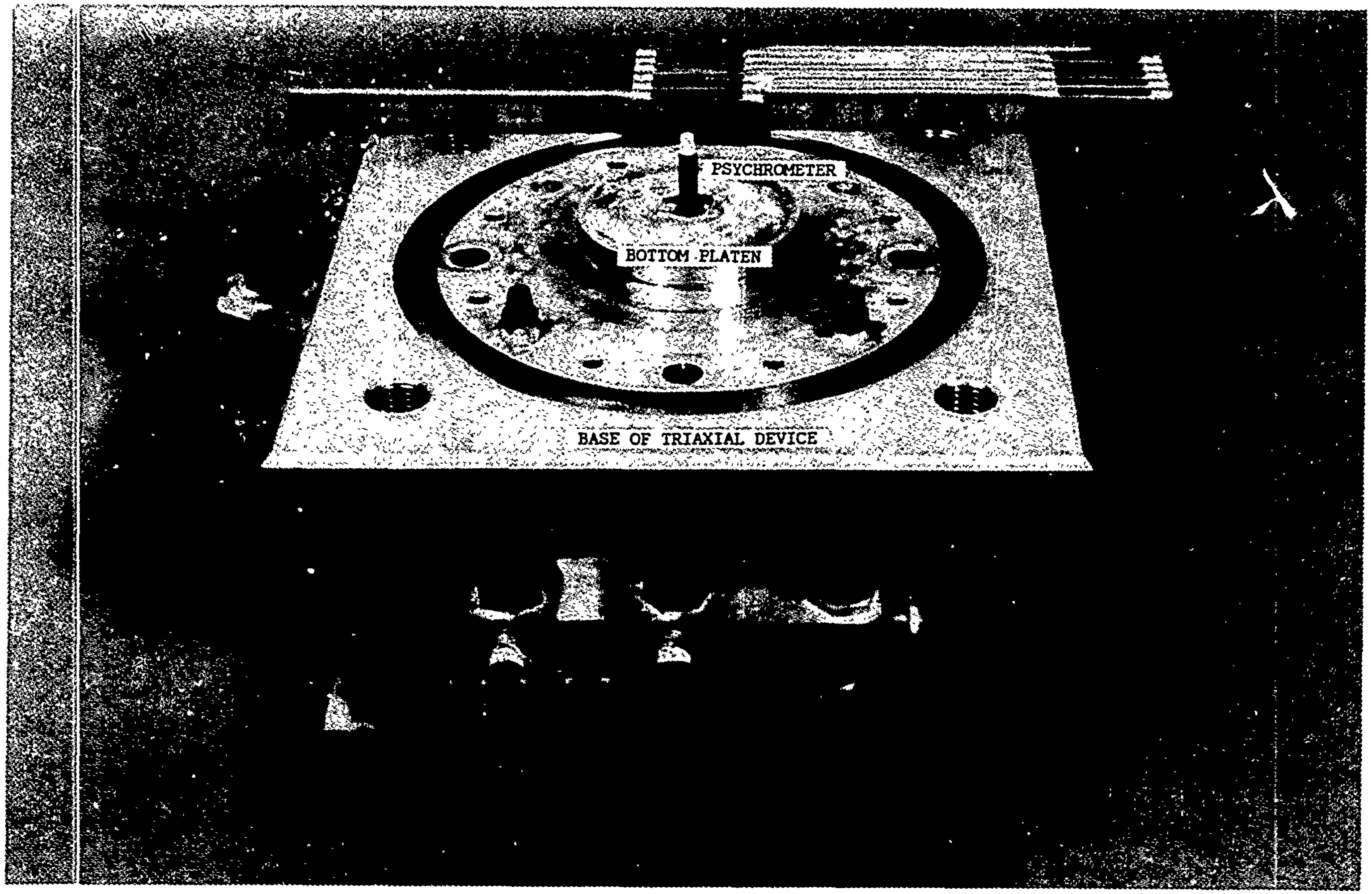

FIG. 21. Psychrometer mounted into the base of a triaxial apparatus.

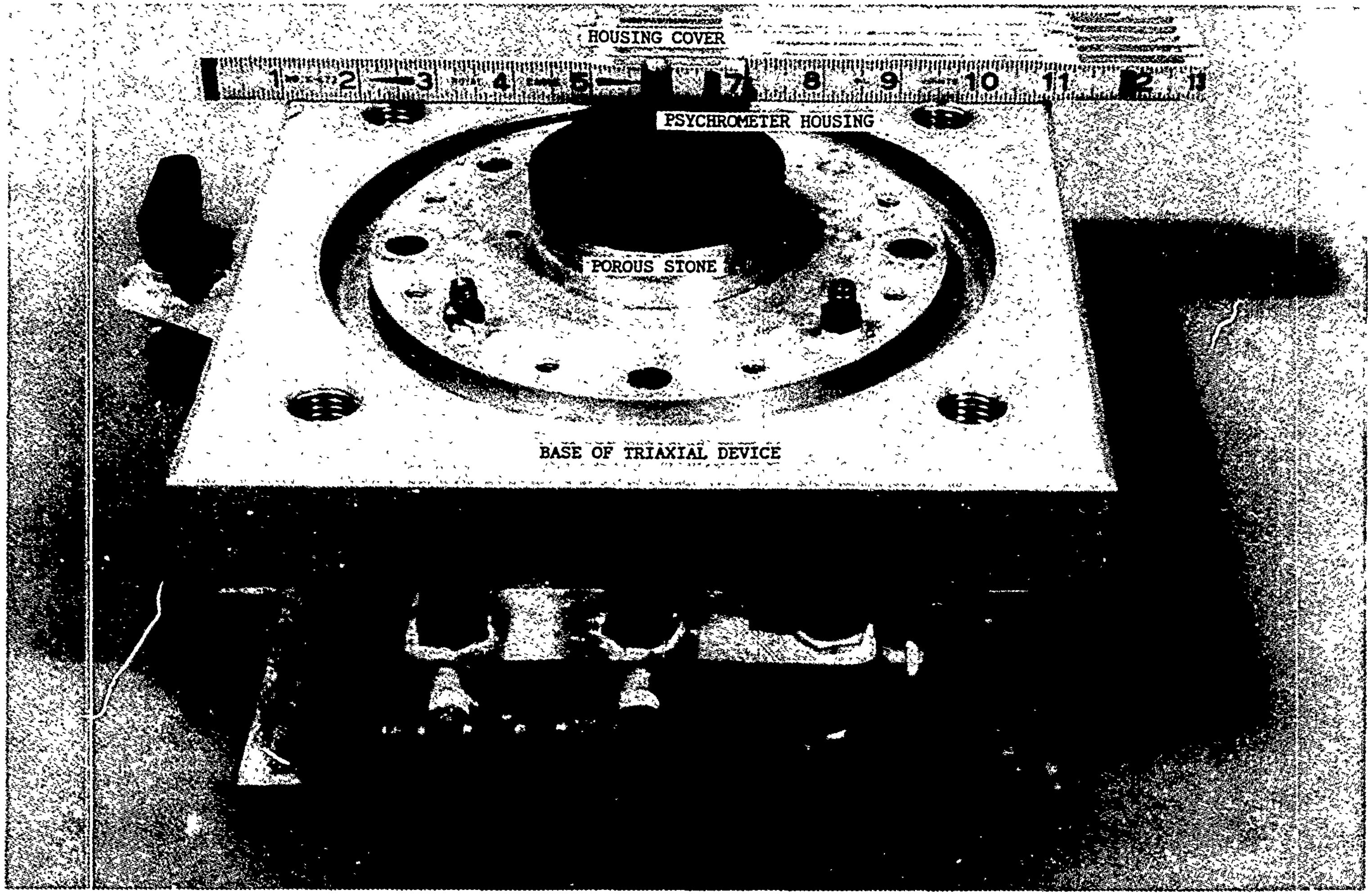

FIG. 22. Psychrometer housing mounted into the base of a triaxial apparatus.

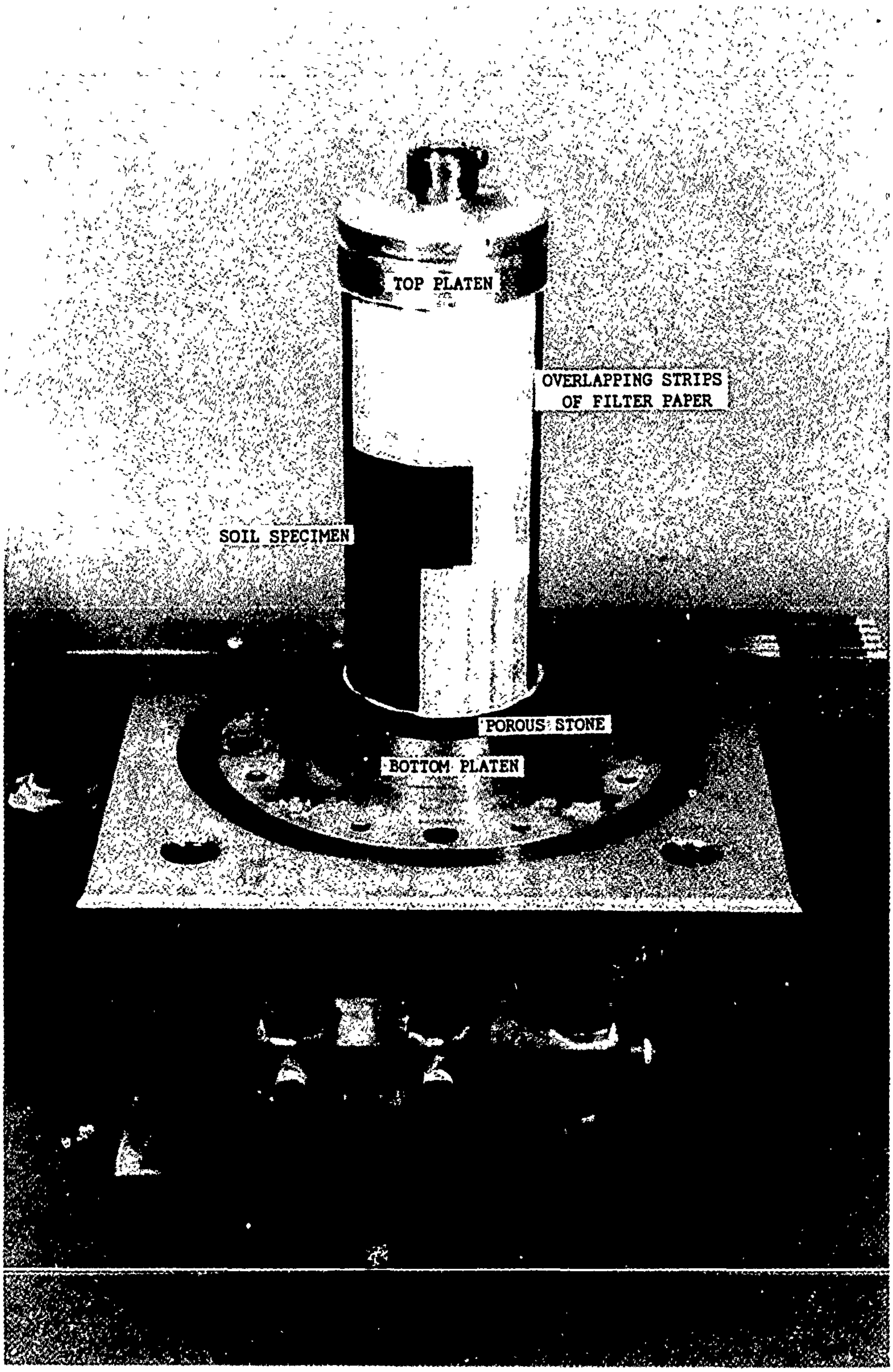

FIG. 23. Placement of overlapping strips of filter paper on a compacted specimen of buckshot clay.

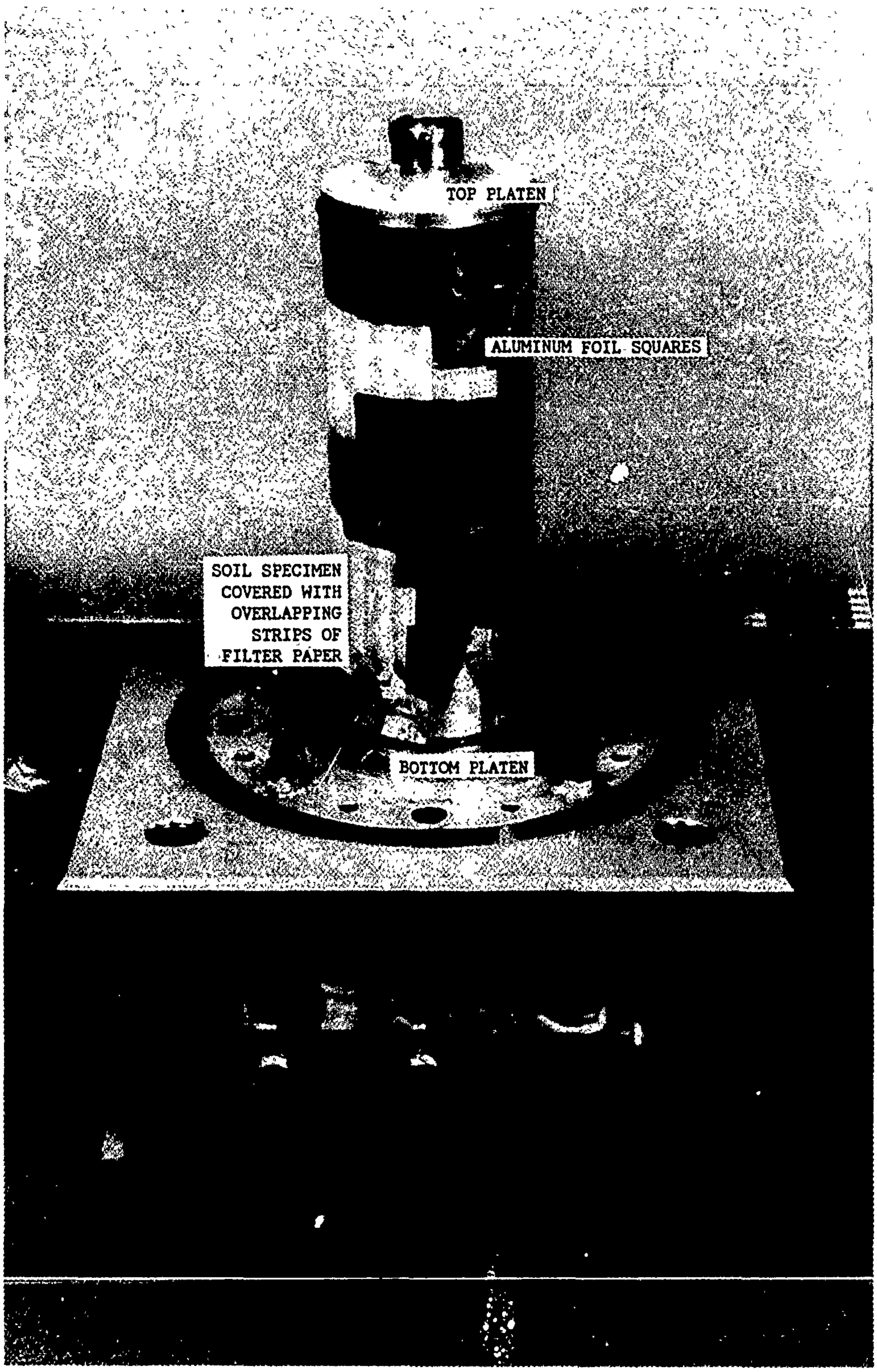

FIG. 24. Placement of aluminum foil squares on a compacted specimen of buckshot clay.

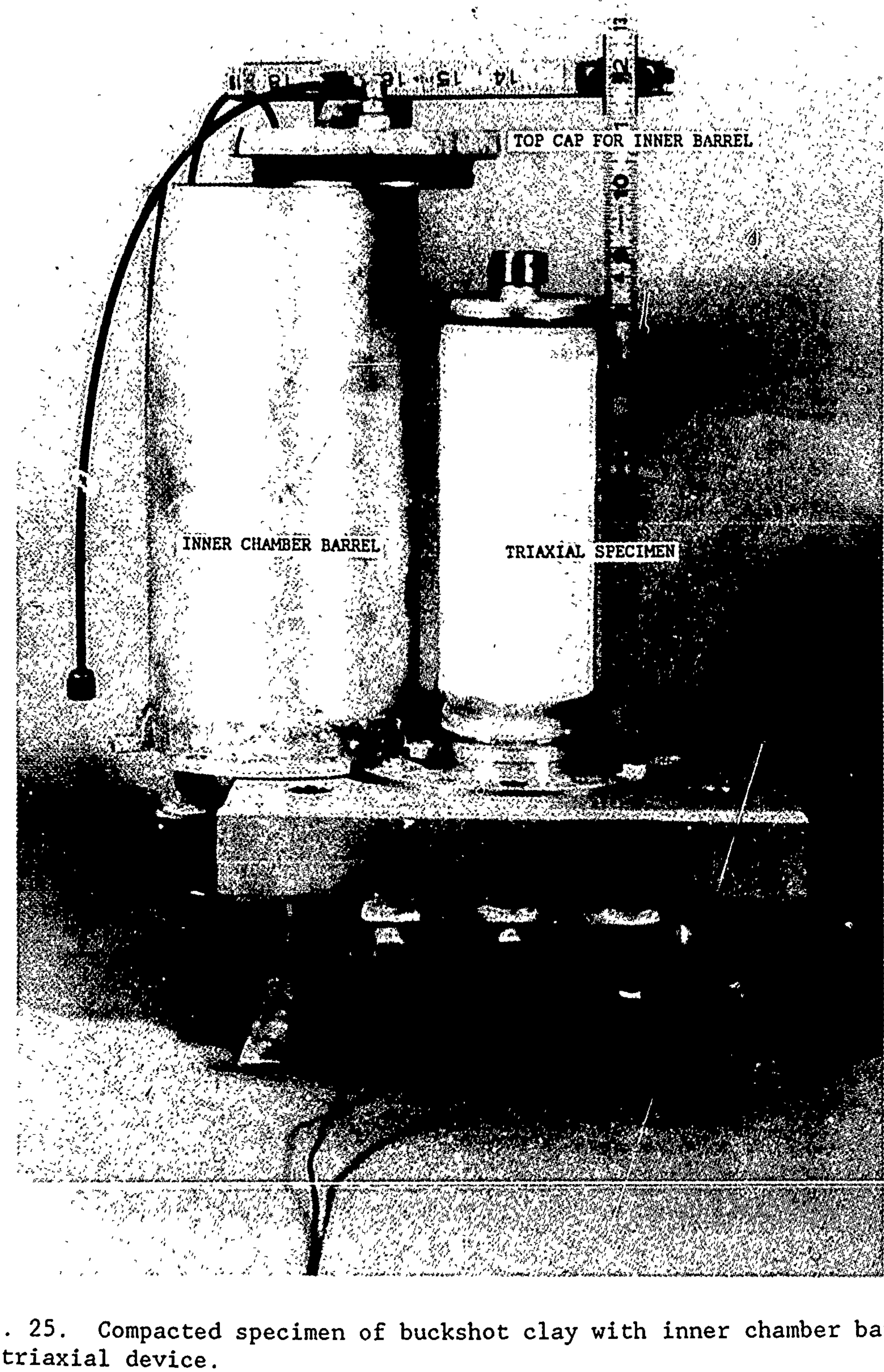

FIG. 25. Compacted specimen of buckshot clay with inner chamber barrel of triaxial device.

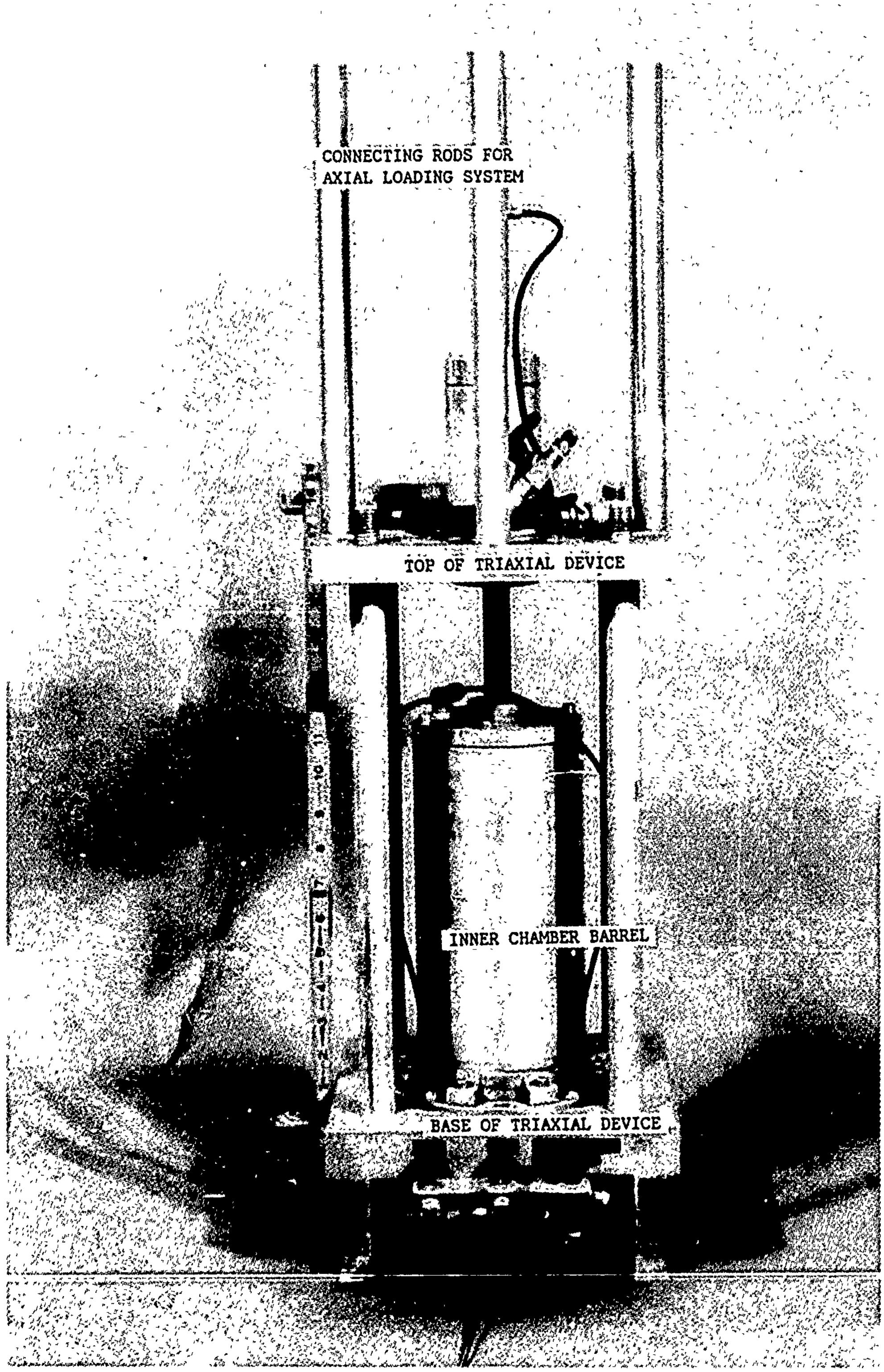

FIG. 26. Assembly of triaxial apparatus for testing unsaturated soil.

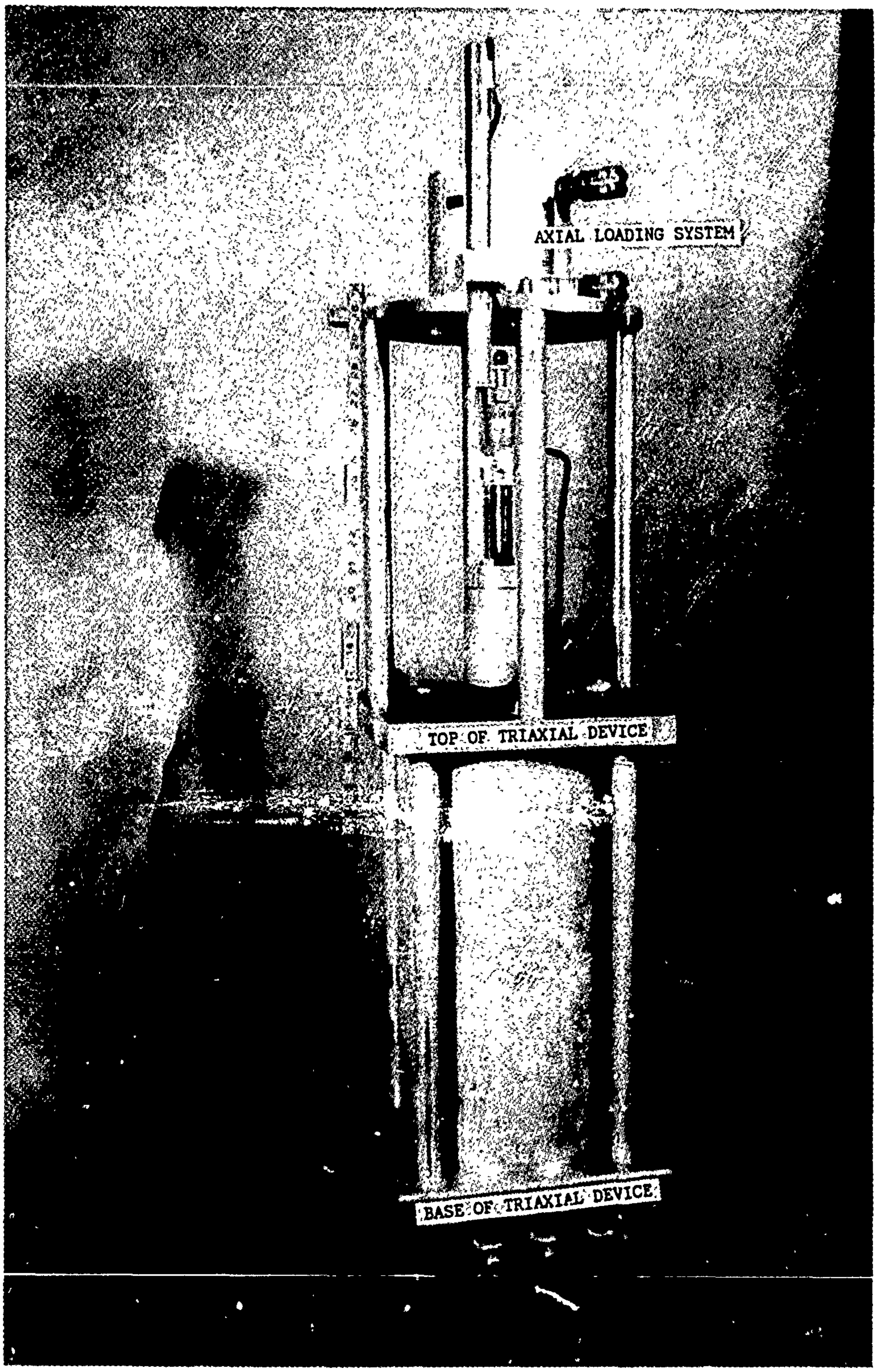

FIG. 27. Assembled triaxial apparatus.

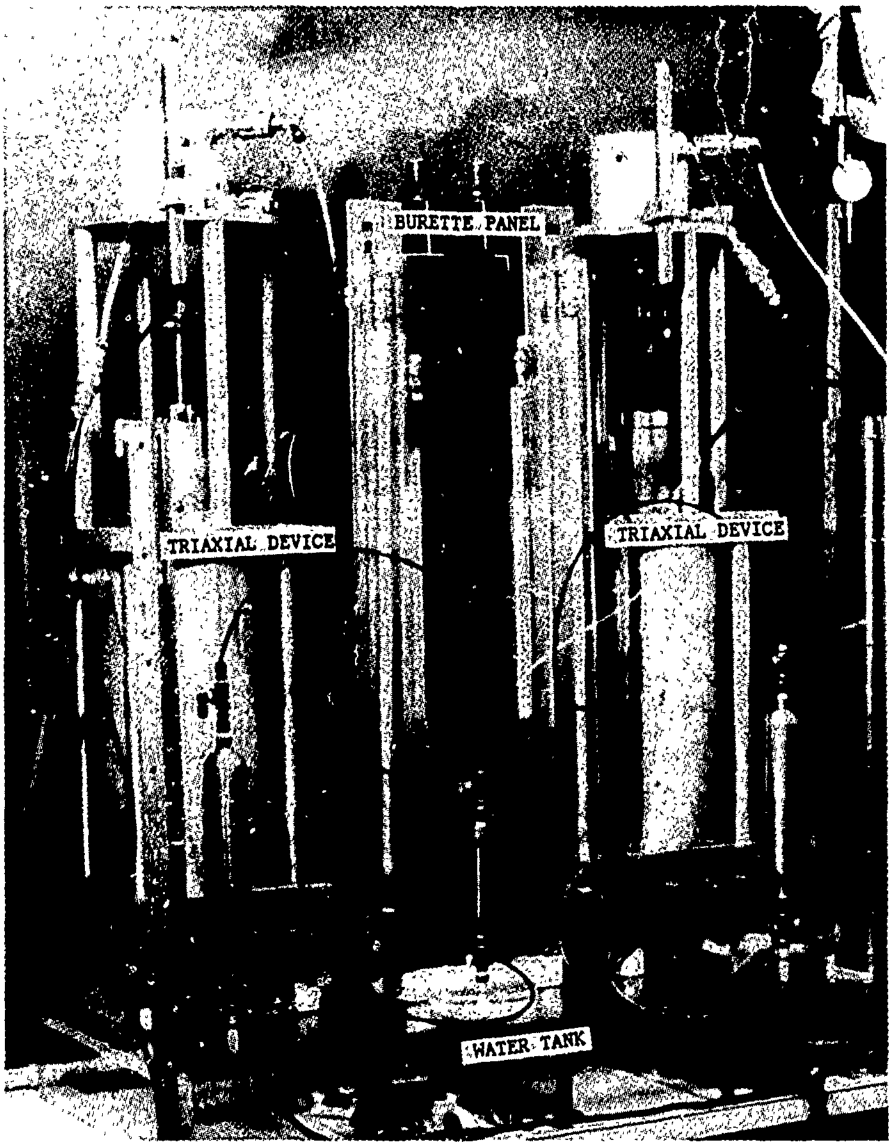

FIG. 28. Triaxial test devices in water bath.

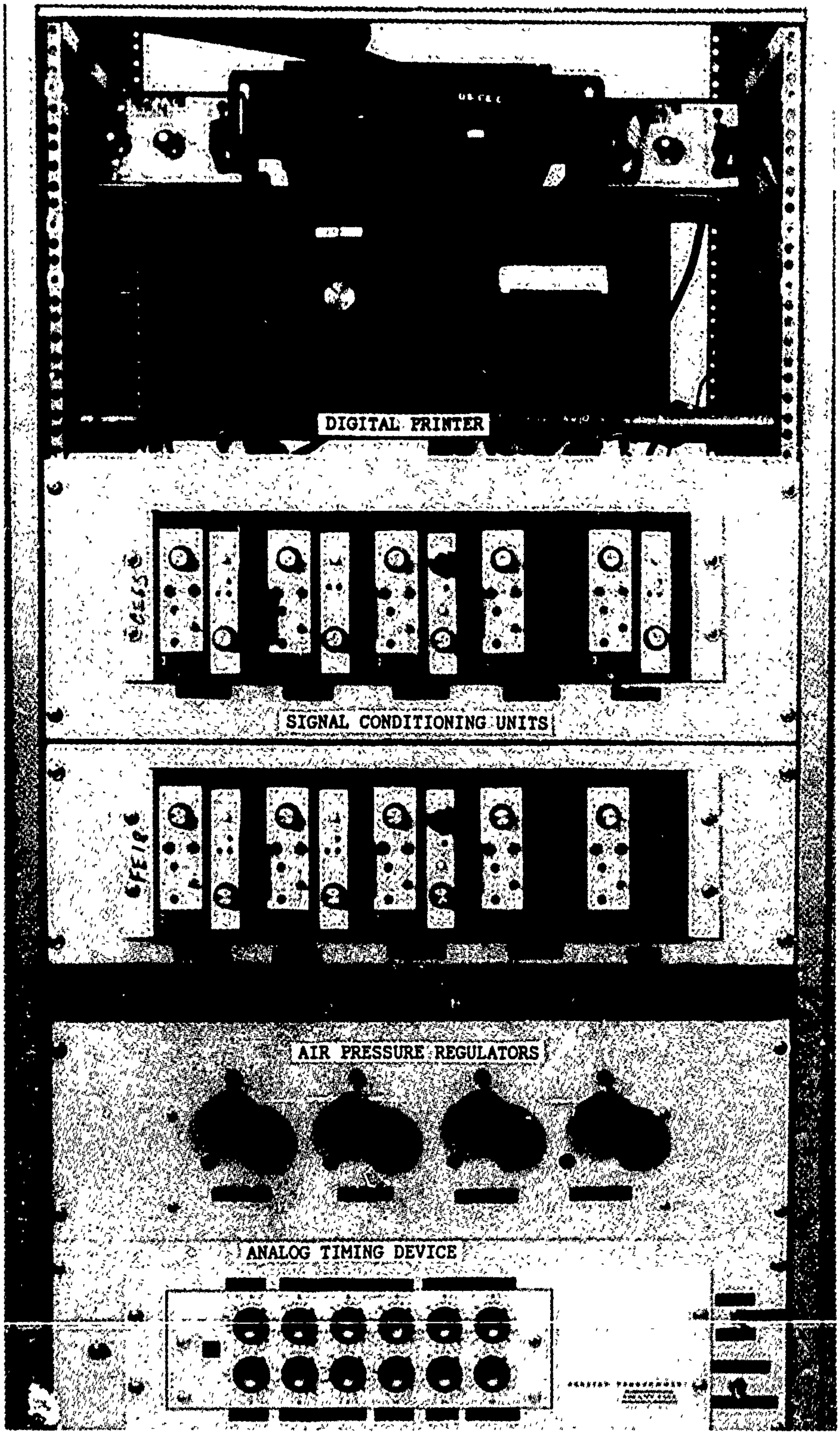

FIG. 29. Instrumentation rack and data acquisition system for testing unsaturated triaxial specimens.

TEST RESULTS AND ANALYSIS OF DATA

Consolidation Tests

Twenty-one specimens, including six specimens which were treated with KCl prior to compaction, were tested as one dimensional consolidation tests. Each specimen was identified using the nomenclature described below. For example, the code for specimen 1D-18-FS-28.9 was:

"1D" identified the test as a one dimensional consolidation test

"18" was the estimated value of solute suction in tons per square foot (tsf) based upon the weight of KCl added to the pore water

"FS" identified the initial boundary conditions imposed upon the test specimen

"28.9" was the initial water content of the test specimen expressed as a percentage.

The term "FS" identified a free swell test specimen, "NS" identified the no swell or constant volume test specimen, and "DR" identified the specimen which was tested at its compacted or natural water content condition.

Consolidation of Buckshot Clay

The results of one dimensional consolidation tests for three specimens compacted at a nominal water content of 26 percent to an initial void ratio of approximately 0.76 are presented in Figure 30. The data are expressed as void ratio, e, versus the logarithm of applied stress, (σ_1 - u), where u is the pore air pressure for unsaturated specimens or pore water pressure for saturated specimens. For these tests, u was assumed to be zero for both saturated and unsaturated specimens because the tests were conducted slowly to allow pore pressures to dissipate. The consolidation relationships for the free swell specimen, identified as 1D-00-FS-25.9, for the no swell or constant volume specimen, identified as 1D-00-NS-26.0, and for the unsaturated or natural water content specimen, identified as 1D-00-DR-25.4, were similar. For each of these specimens, the compression index, which is the slope of the void ratio

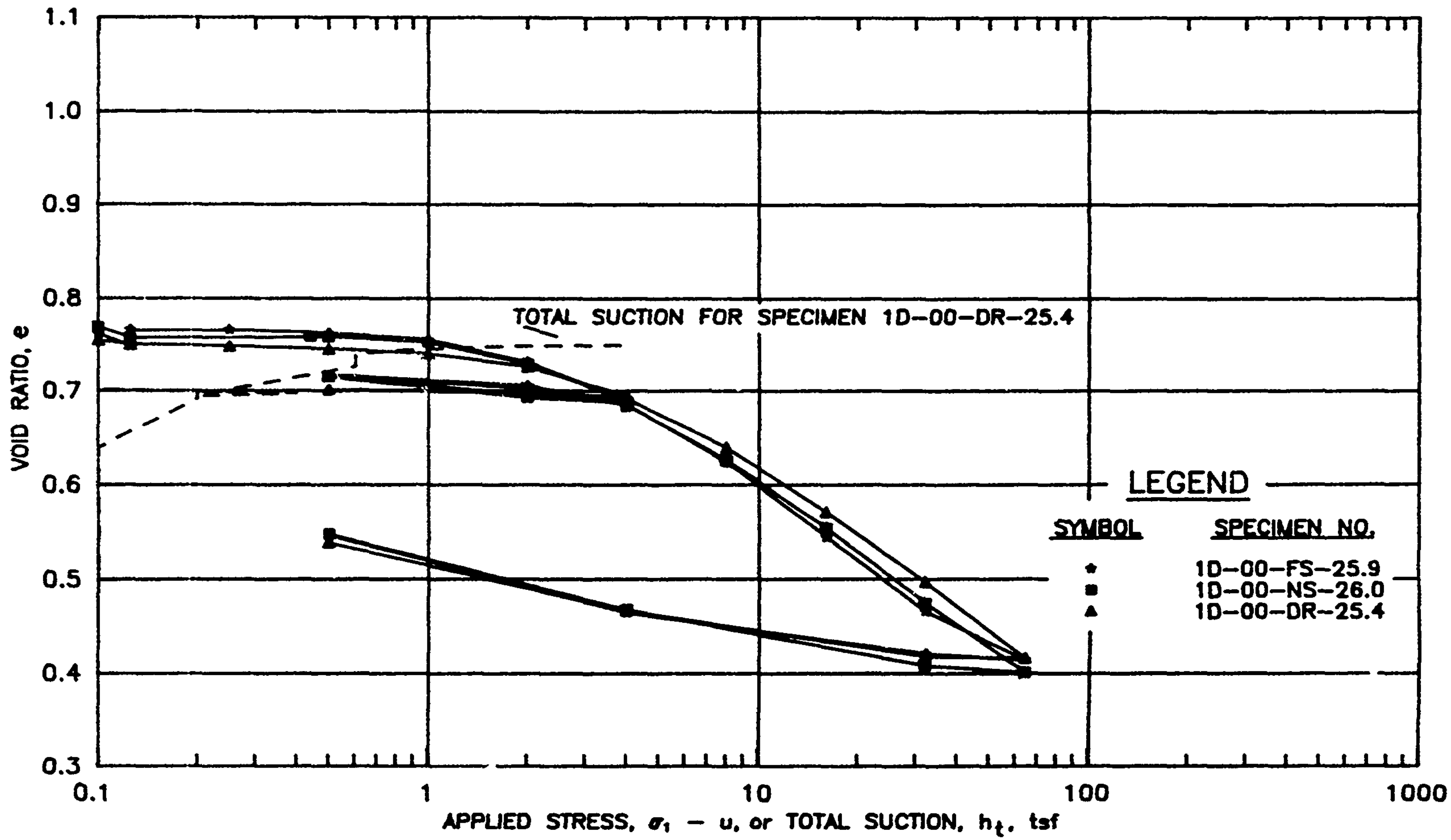

FIG. 30. One dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 26 percent. (1 tsf = 96 kPa)

versus the logarithm of applied stress relationship, was nearly zero for applied stresses less than 1 tsf (100 kPa) but increased to approximately 0.25 at stress levels in excess of 10 tsf (960 kPa).

Total suction for the unsaturated specimen is superimposed on Figure 30. As the specimen consolidated, measured values of suction decreased from an initial value of 4 tsf (380 kPa) at a void ratio of 0.76 to 0.2 tsf (20 kPa) at a void ratio of 0.69. As consolidation of the specimen continued, it is likely that pore water was squeezed from the soil because the calculated degree of saturation exceeded 100 percent. For this condition, matrix suction would be approximately zero; measured values of suction determined by the psychrometer would be due to solute suction, as indicated by Equation 6. Although the accuracy of a suction measurement of 0.2 tsf (20 kPa) is questionable because psychrometers are not reliable for measuring small values of suction, this value compares well with the calculated value of solute suction of 0.1 tsf (10 kPa) which was determined by the saturation extract method (Black, 1965). From these data, it was concluded that solute suction in Vicksburg buckshot clay was negligible and unless otherwise noted, matrix suction was assumed to be equivalent to total suction when unsaturated strength parameters, such as χ or ϕ^b, were evaluated.

The results of tests on specimens 1D-00-FS-20.0, 1D-00-NS-20.2 and 1D-00-DR-19.0 which were subjected to free swell, constant volume and natural water content conditions, respectively, are presented in Figure 31. These specimens were compacted to an initial void ratio of 0.9 at a nominal water content of 20 percent. Initially, the compression indices for the inundated specimens were approximately zero but increased to 0.26 at an applied stress of 2 tsf (190 kPa). Because the consolidation relationship for specimen 1D-00-FS-20.0 was curvilinear, the compression index gradually decreased to 0.21 at an applied stress of 20 tsf (1.9 MPa). Unfortunately, the consolidation characteristics of specimen 1D-00-NS-20.2 were suspect for applied stresses greater than 2 tsf (190 kPa) because the top loading platen was binding. The consolidation relationship for the unsaturated specimen was somewhat different than the relationships for saturated specimens. Initially, the compression index was nearly zero but increased to 0.5 at an applied

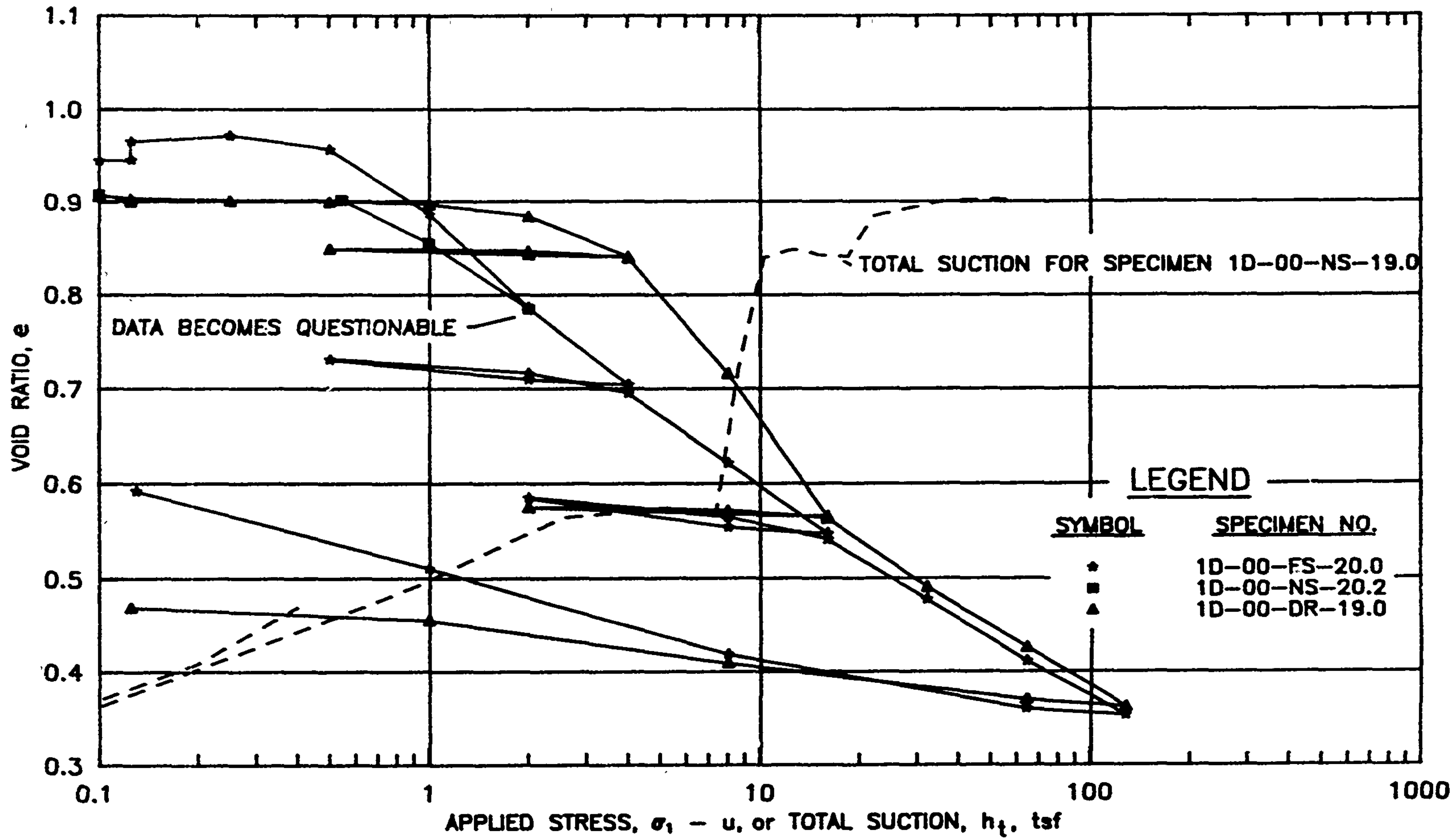

FIG. 31. One dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 20 percent. (1 tsf = 96 kPa)

stress of 8 tsf (770 kPa). At an applied stress of 16 tsf (1.5 MPa) and a void ratio of 0.56, which corresponded to a degree of saturation of approximately 90 percent, the compression index decreased abruptly to 0.24 and then continued to decrease to 0.21 at an applied stress of 128 tsf (12.3 MPa). Perhaps this behavior was the result of pore water being squeezed from the specimen. At high degrees of saturation, it is likely that water was being squeezed from the specimen; for this condition, the consolidation characteristics of natural water content specimens would be similar to the consolidation characteristics of inundated specimens.

Total suction for the unsaturated specimen was also presented in Figure 31. In general, measured values of suction decreased as the specimen consolidated. At a void ratio of 0.84, suction was approximately 10 tsf (960 kPa). When the specimen had consolidated to a void ratio of 0.56, suction had decreased to 7 tsf (670 kPa). At a void ratio of 0.36, suction had decreased to 0.1 tsf (10 kPa).

The results of tests on specimens 1D-00-FS-21.0, 1D-00-NS-21.0 and 1D-00-DR-22.1 conducted as free swell, constant volume and the natural water content tests, respectively, are presented in Figure 32. These specimens were compacted to an initial void ratio of 0.8 at a nominal water content of 21 percent. The test results were similar to the data presented in Figure 31. Initial values of the compression indices of inundated specimens were approximately zero but gradually increased to a maximum value of 0.23 at an applied stress of 1 tsf (100 kPa) and then decreased slightly at larger consolidation stresses. The consolidation relationship for the unsaturated specimen was similar to the consolidation relationship for the unsaturated specimen presented in Figure 31. Initially, the compression index was about zero but increased to 0.45 at an applied stress of 8 tsf (770 kPa). At an applied stress of 16 tsf (1.5 MPa), which corresponded to a void ratio of 0.55 and a degree of saturation of 100 percent, the compression index decreased abruptly to 0.27 and continued to decrease to a minimum value of 0.22 at an applied stress of 128 tsf (12.3 MPa). As compared to the results for other unsaturated specimens, the measured values of total suction for this specimen also decreased as consolidation occurred.

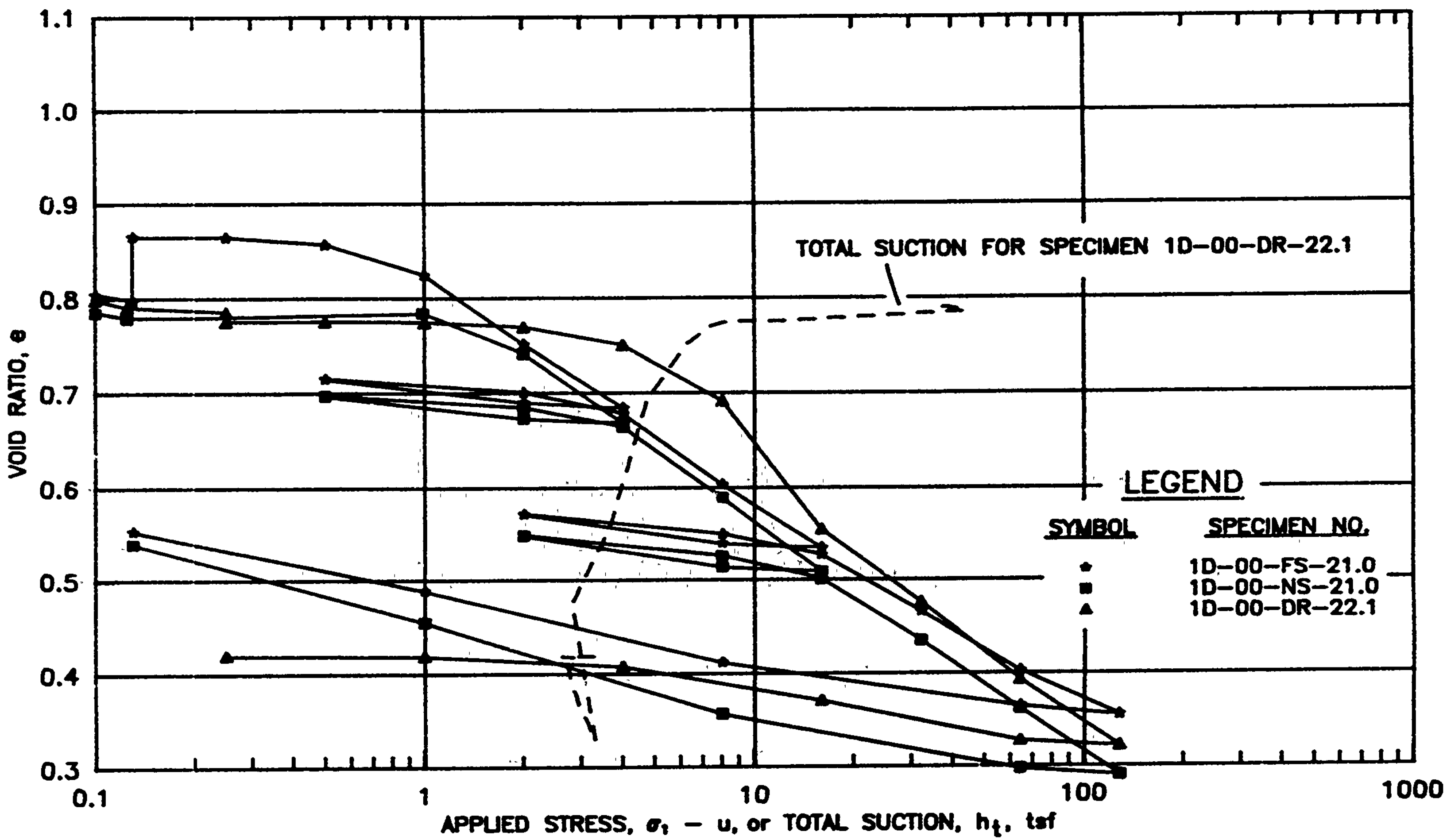

FIG. 32. One dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 21 percent. (1 tsf = 96 kPa)

However, the minimum value of suction was 2.8 tsf (270 kPa). This value was much larger than anticipated and should be considered as suspect. It is believed that perhaps the gain control knob on the microvoltmeter was inadvertently changed during the test.

The results of tests on specimens 1D-00-FS-17.4, 1D-00-NS-16.4 and 1D-00-DR-15.9 for free swell, constant volume and natural water content conditions, respectively, are presented in Figure 33. These specimens were compacted to an initial void ratio of approximately 1.1 at a nominal water content of 16 percent. The compression indices for the inundated specimens increased from initial values which were approximately zero to 0.37 at an applied stress of 0.5 tsf (50 kPa) before decreasing as the consolidation stresses were increased. However, the results for specimens 1D-00-NS-16.4 and 1D-00-FS-17.4 became questionable at applied stresses of approximately 2 and 8 tsf (190 and 770 kPa), respectively, because the top loading platens were binding. The consolidation relationship for the unsaturated specimen was similar to the consolidation relationships for specimens 1D-00-DR-19.0 and 1D-00-DR-22.1. Initially, the compression index was about zero but increased to a maximum value of 0.56 at an applied stress of 8 tsf (770 kPa). For stresses in excess of 32 tsf (3.1 MPa), which corresponded to a degree of saturation of approximately 90 percent, the compression index decreased to 0.21. Total suction decreased as the unsaturated specimen was consolidated. For example, the suction of 8 tsf (770 kPa), which was measured at a void ratio of 0.48, decreased rapidly to a minimum value of 0.5 tsf (50 kPa) at a void ratio of 0.37. This behavior was similar to the behavior for other unsaturated specimens.

The results of tests on specimens compacted to an initial void ratio of 0.63 at a nominal water content of 21 percent and identified as 1D-00-FS-20.9, 1D-00-NS-20.4 and 1D-00-DR-20.5 for the free swell, constant volume and the natural water content specimens, respectively, are presented in Figure 34. Initial values of the compression indices for all specimens were approximately zero but gradually increased to a maximum value of 0.24 as the consolidation stresses were increased to

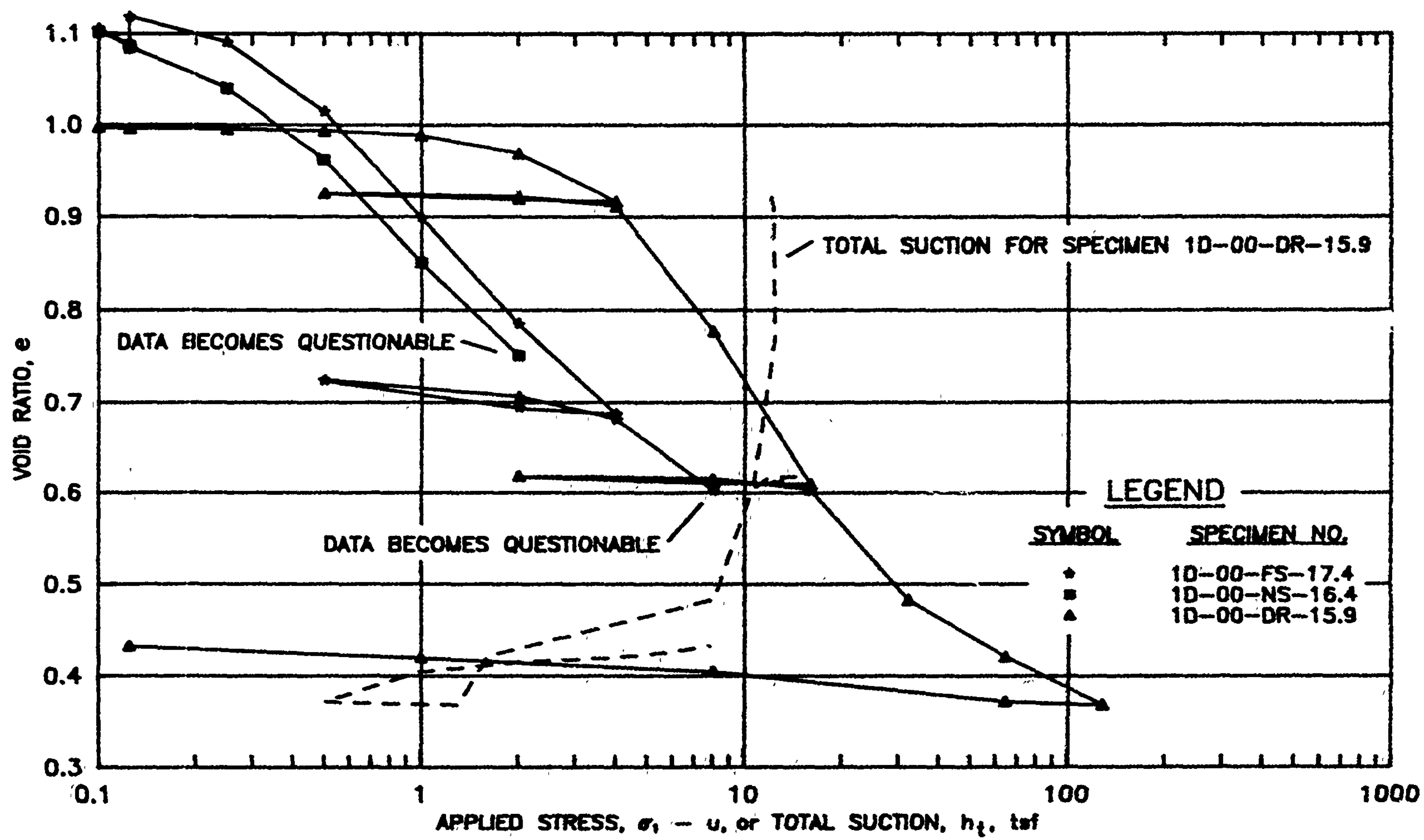

FIG. 33. One dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 17 percent. (1 tsf = 96 kPa)

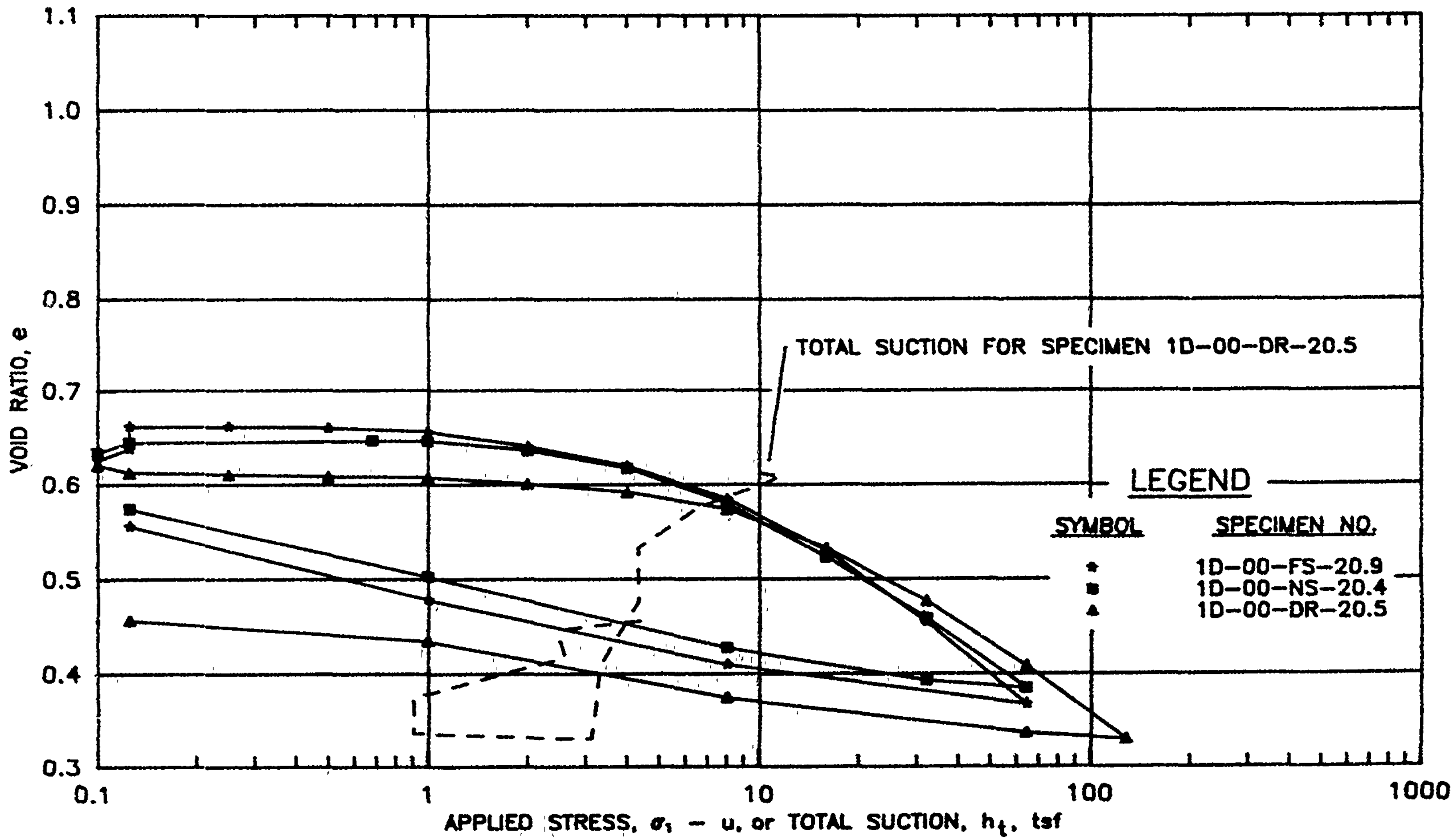

FIG. 34. One dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 21 percent using the high compactive effort. (1 tsf = 96 kPa)

128 tsf (12.3 MPa). As the unsaturated specimen was consolidated, suction decreased from 11 tsf (1.1 MPa) at a void ratio of 0.61 to less than 1 tsf (100 kPa) at a void ratio of 0.34.

Consolidation of Clay Treated with Potassium Chloride

The results of tests on three specimens of Vicksburg buckshot clay which were treated with KCl to produce a value of solute suction of about 18 tsf (1.7 MPa) are presented in Figure 35. The specimens, identified as 1D-18-FS-28.9, 1D-18-NS-28.7 and 1D-18-DR-28.0 for the free swell, constant volume and the natural water content specimens, respectively, were compacted to a void ratio of 0.85 at a water content of 28 percent. Initial values of the compression indices were approximately zero but gradually increased to 0.25 at an applied stress of 8 tsf (770 kPa). In general, the consolidation characteristics were similar to the consolidation behavior of untreated specimens compacted at a water content of 26 percent, which are presented in Figure 30.

The measured values of suction as the unsaturated specimen was consolidated were much different than anticipated. For example, total suction for specimen 1D-18-DR-28.0 decreased from an initial value of 25 tsf (2.4 MPa) at a void ratio of 0.85 to 6 tsf (580 kPa) at a void ratio of 0.71 and an applied stress of 4 tsf (380 kPa). However, as additional consolidation occurred due to increased loads, total suction increased to 14 tsf (1.3 MPa) at a void ratio of 0.49 and an applied stress of 32 tsf (3.1 MPa). As the specimen was rebounded, suction decreased slightly. For this specimen, the calculated degree of saturation was greater than 100 percent for void ratios less than 0.76 and applied stresses in excess of 2 tsf (190 kPa).

The results of consolidation tests on three specimens of Vicksburg buckshot clay which had been treated with KCl to produce a solute suction of about 18 tsf (1.7 MPa) are presented in Figure 36. The specimens, identified as 1D-18-FS-20.8, 1D-18-NS-20.7 and 1D-18-DR-20.0 for the free swell, constant volume and the natural water content specimens, respectively, were compacted to a void ratio of 0.82 at a nominal water content of 20 percent. Initial values of the compression indices for all specimens were about zero but gradually increased to 0.27 at an

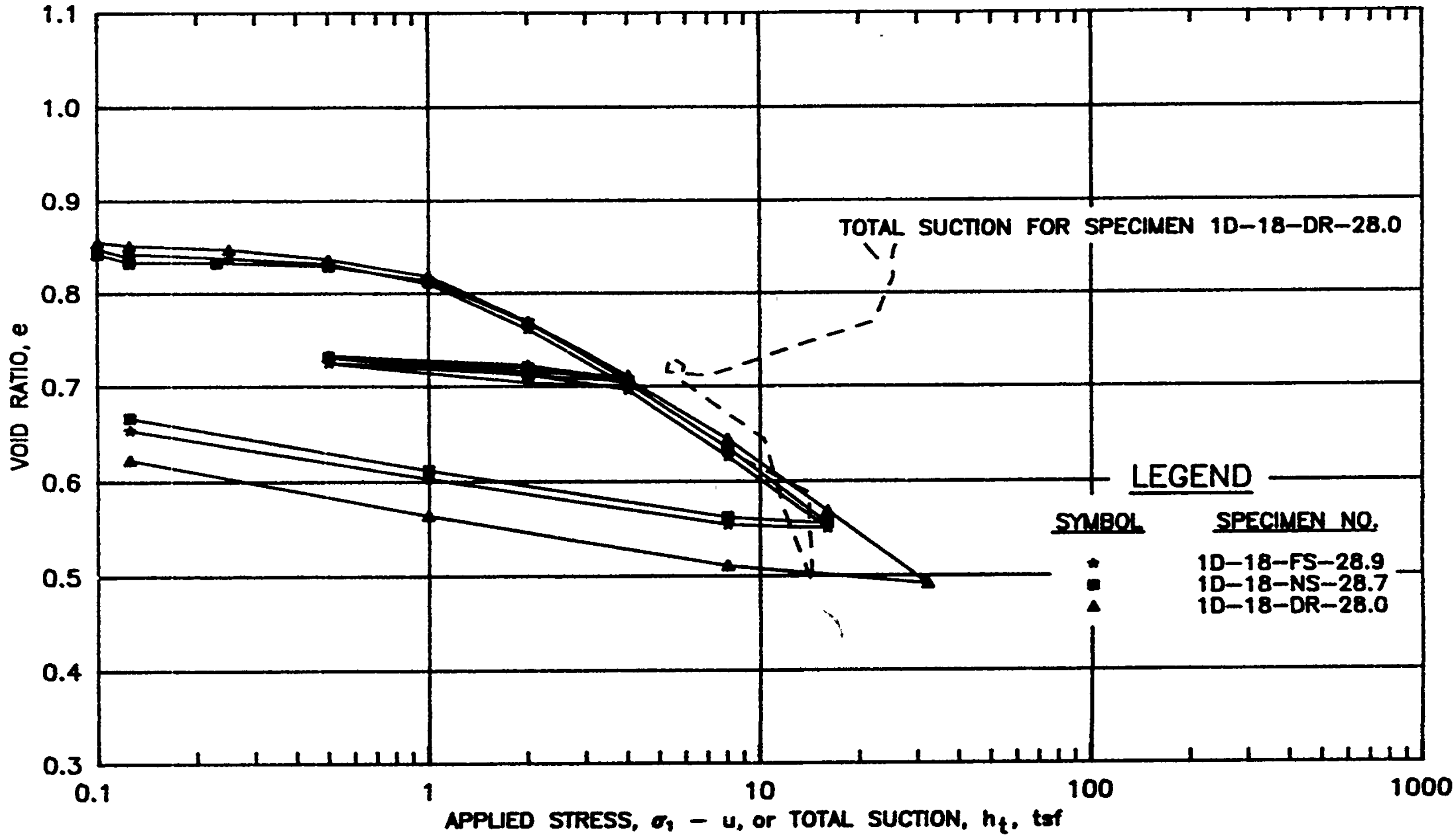

FIG. 35. One dimensional consolidation test results for specimens of buckshot clay treated with potassium chloride prior to compaction at a nominal water content of 28 percent. (1 tsf = 96 kPa)

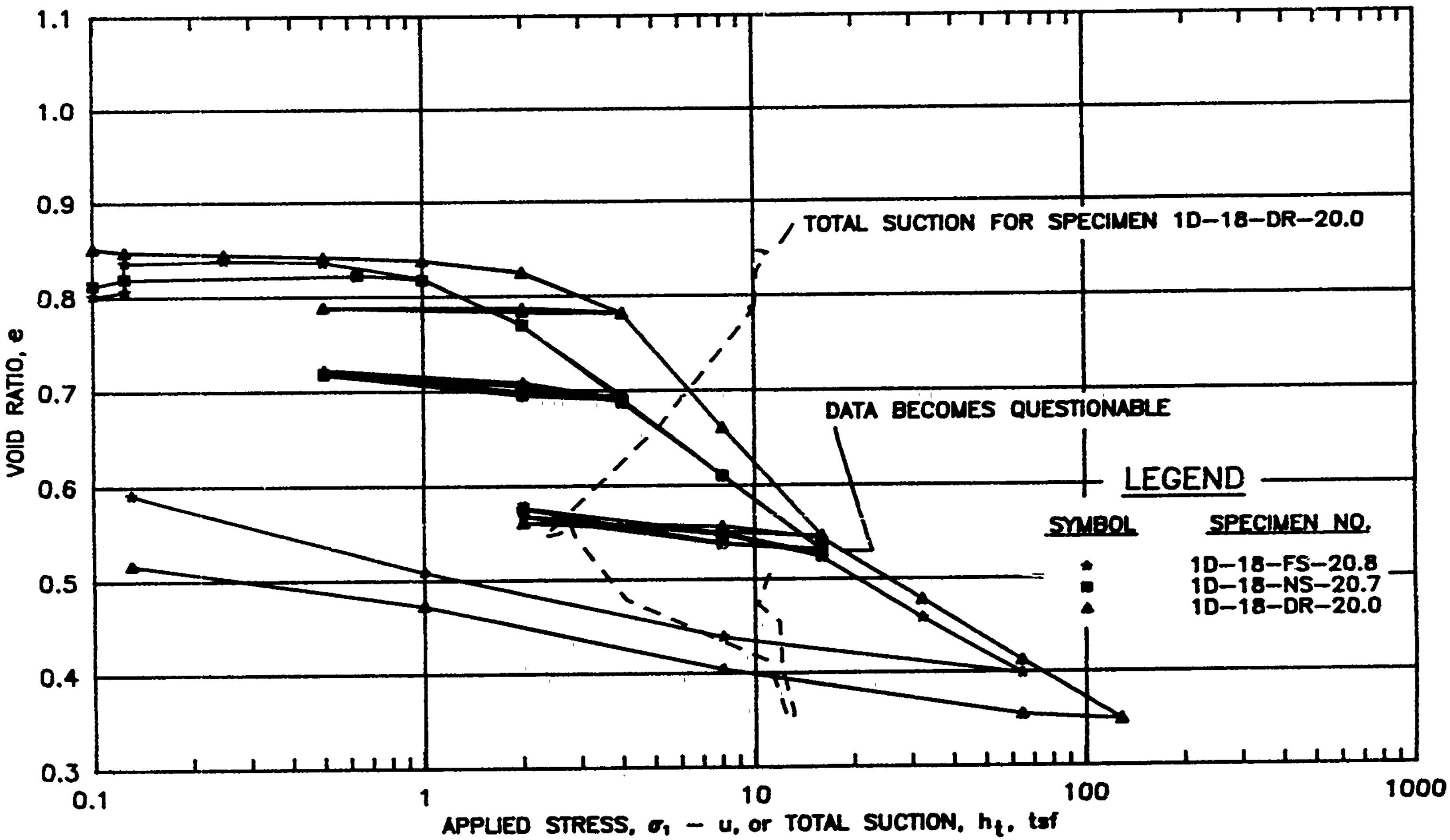

FIG. 36. One dimensional consolidation test results for specimens of buckshot clay treated with potassium chloride prior to compaction at a nominal water content of 20 percent. (1 tsf = 96 kPa)

applied stress of 4 tsf (380 kPa) for the inundated specimens and 0.40 at an applied stress of 8 tsf (770 kPa) for the natural water content specimen. At an applied stress of 32 tsf (3.1 MPa), the compression indices for all specimens had decreased to approximately 0.22. Total suction for specimen 1D-18-DR-20.0 was qualitatively similar to the measured suction for specimen 1D-18-DR-28.0. Suction decreased from an initial value of 11 tsf (1.0 MPa) at a void ratio of 0.84 to 2 tsf (190 kPa) at a void ratio of 0.55 and an applied stress of 16 tsf (1.5 MPa). As consolidation of the specimen continued, total suction increased to a maximum value of 13 tsf (1.2 MPa) at a void ratio of 0.35 and an applied stress of 128 tsf (12.3 MPa). As the specimen was rebounded, suction decreased slightly.

Discussion

From the data reported herein, it was obvious that the water content of the specimens as well as the treatment of soil with potassium chloride influenced the consolidation characteristics of buckshot clay. For inundated specimens, a curvilinear void ratio versus applied stress relationship, similar to the results for specimen 1D-00-FS-20.0, which is presented in Figure 31, existed. For tests conducted on specimens which were compacted at a nominal water content of 26 percent and consolidated at the natural water content, the consolidation relationship was similar to the data for specimen 1D-00-DR-25.4, which is presented in Figure 30. For tests conducted on specimens which were compacted at a nominal water content of 20 percent and consolidated at the natural water content, the consolidation relationship was similar to the data for specimen 1D-00-DR-19.0, which is also presented in Figure 31. A fourth relationship was observed for specimen 1D-00-DR-15.9, which is presented in Figure 33. Provided the degree of saturation was less than approximately 90 percent, a larger stress was required to consolidate specimen 1D-00-DR-15.9 to a given void ratio than the stress required to consolidate specimen 1D-00-DR-19.0 to the same void ratio. A fifth consolidation relationship was observed for treated specimen 1D-18-DR-20.0 which is presented in Figure 36. As compared to the results for untreated specimens, 1D-00-FS-20.0, 1D-00-DR-19.0 and

1D-00-DR-22.1 which are presented in Figures 31 and 32, the stress required to consolidate specimen 1D-18-DR-20.0 to a given void ratio was less than the stress required to consolidate the unsaturated specimens but greater than the stress required to consolidate the inundated specimen to the same void ratio.

Although the consolidation relationships for treated and untreated specimens tested at natural water contents were qualitatively similar and the preconsolidation stresses, as determined by the Casagrande construction technique, were about 4 tsf (380 kPa), the consolidation relationships and compression indices for these specimens were quantitatively different. Maximum values of compression indices ranged from 0.56 to 0.45 for untreated specimens 1D-00-DR-15.9 and 1D-00-DR-19.0, respectively, as compared to 0.40 for treated specimen 1D-18-DR-20.0.

The void ratio versus applied stress relationships for specimens 1D-00-FS-20.0, 1D-00-DR-15.9, 1D-00-DR-19.0 and 1D-18-DR-20.0 were expressed arithmetically as shown in Figure 37. The coefficients of compressibility, a_v, for the natural water content specimens were similar for applied stresses ranging from 4 to 16 tsf (0.4 to 1.5 MPa) and the consolidation relationships were, for practical purposes, separated by equal increments of void ratio. The applied stress required to consolidate an unsaturated specimen to a given void ratio increased as the compaction water content was decreased. For example, the applied stresses required to consolidate specimens 1D-00-FS-20.0, 1D-00-DR-19.0 and 1D-00-DR-15.9 to a void ratio of 0.78 were 2.1, 6.6 and 7.9 tsf (200, 630 and 760 kPa), respectively. For each of these tests, the compression index inferred the specimen was being consolidated along a pseudo "virgin compression curve." For comparison, the applied stress required to consolidate treated specimen 1D-18-DR-20.0 to a void ratio of 0.78 was 4.1 tsf (390 kPa). Based upon these results, the treatment of buckshot clay with potassium chloride affected the consolidation characteristics of the soil. However, additional test data are desirable as only two specimens were tested at two water contents.

Test results were examined for quantitative or qualitative relationships to describe the influence of suction on the consolidation of unsaturated specimens of buckshot clay. Measured values of suction

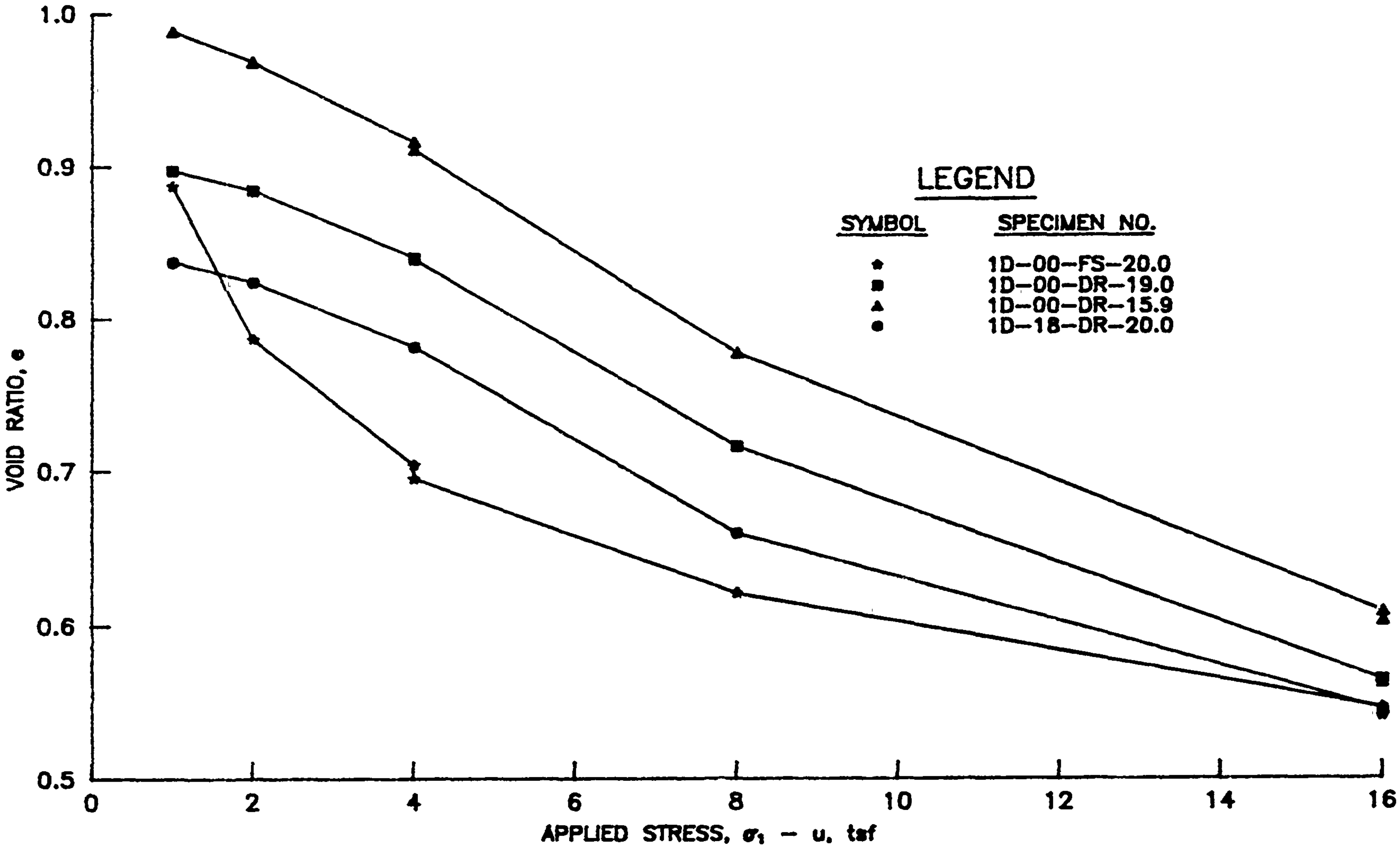

FIG. 37. Typical void ratio versus applied stress relationships for unsaturated and inundated specimens of buckshot clay. (1 tsf = 96 kPa)

were expressed as a function of void ratio and the degree of saturation. A unique relationship was not obvious. Differences of void ratios between saturated and unsaturated specimens as a function of suction were also examined. Again, the data showed much scatter and no unique relationships were observed. The most significant observation was that suction decreased rapidly as the degree of saturation exceeded approximately 90 percent. Based upon a review of the literature and observations during the investigation reported herein, it seemed reasonable to assume that the influence of suction on the consolidation of unsaturated soil was a variable, similar to Bishop's χ factor versus degree of saturation relationship. The data indicated the efficiency of suction was relatively small for large values of suction but increased as suction decreased.

The data were also examined for a possible explanation of the unanticipated behavior of the suction versus void ratio relationships as treated specimens were consolidated at natural water content conditions. Recall that total suction for specimens 1D-18-DR-28.0 and 1D-18-DR-20.0 decreased during the initial portions of the consolidation tests but increased as water began to drain from each specimen. Guided by the discussions of the results of suction tests on sodium grundite (Edil and Motan, 1984; Richards, Emerson and Peter, 1986), it is believed that salt sieving occurred (Bolt and Lagerwerff, 1965). The anomaly was apparently a result of the adsorption of the cations on the clay particle surfaces which caused a lowering of the ionic concentration in the bulk water. For this condition, the measured values of solute suction were less than the theoretical values used in the preparation of the solutions. An explanation follows.

At the beginning of the consolidation test, total suction may have been dominated by matrix suction. As each specimen was consolidated, matrix suction decreased as the void ratio of the specimen decreased and the degree of saturation increased. At high degrees of saturation, matrix suction approached zero as pore water began to drain from the soil. As drainage continued, cations were expelled from soil. The increased concentration of potassium cations in the pore fluid caused an

increase of solute suction. When the specimens were rebounded, potassium cations were readily adsorbed by the soil which caused the solute suction to again decrease.

Because a unique relationship to describe the influence of suction on the consolidation behavior of unsaturated specimens of buckshot clay could not be determined, efforts to measure suction were reassessed. Two problems were identified:

(a) Values of emf which had been corrected for temperature differences using Equation 18 were consistently larger in the afternoon when the ambient temperatures in the laboratory were warmer than in the morning when the ambient temperatures in the laboratory were cooler.

(b) Although fairly large values of suction were measured, say 10 to 20 tsf (1.0 to 2.0 MPa), the recorded values of emf were fairly small, usually less than 5 to 10 μvolts.

Based upon these findings, a large tank was constructed to allow the triaxial devices to be submerged in a constant temperature water bath maintained at 25 deg C. A digital recorder was connected to the microvoltmeter which permitted the emf to be recorded to the nearest 0.1 μvolt. A discussion of the water bath and suction measurement system were presented in "Development of Laboratory Testing Equipment."

Equivalent Consolidation Relationship

An examination of the consolidation test results for buckshot clay resulted in a paradox. Although these tests were intended to provide guidance for selecting an equivalent consolidation stress relationship, several consolidation relationships for buckshot clay had been identified: the inundated condition, the unsaturated or natural water content condition for water contents varying from 16 to 25 percent and the natural water content condition for treated specimens. Following a review of Hvorslev's (1961, 1969) and Bishop and Henkel's (1962) articles on the true friction - true cohesion concept, it was concluded that the influence of soil suction on the behavior of unsaturated soil could be evaluated only if the test results were compared to the results obtained for saturated specimens. Hence, an equivalent consolidation stress relationship was developed using consolidation data for

inundated specimens and test data obtained for unsaturated specimens which had been consolidated to high degrees of saturation.

Following a review of notes recorded for each test, such as the magnitude of applied stress at which soil was extruded from the consolidometer and the percentage of soil by dry weight which was extruded, test results for specimens 1D-00-FS-25.9, 1D-00-FS-20.0, 1D-00-NS-26.0, 1D-00-DR-25.4, 1D-00-DR-20.5, 1D-00-DR-19.0, 1D-00-DR-15.9, 1D-18-FS-28.9, 1D-18-NS-28.7, 1D-18-DR-28.0 and 1D-18-DR-20.0 were judged to be of high quality. The void ratio versus applied stress relationships for these specimens provided guidance for developing an equivalent consolidation relationship for the soil. Unfortunately, the test results indicated these specimens were overconsolidated for consolidation stresses less than approximately 8 to 16 tsf (0.8 to 1.5 MPa), which was much greater than the range of applied stresses for most of the triaxial tests. Therefore, additional data for specimens consolidated by low stresses were needed to develop an equivalent consolidation relationship for Vicksburg buckshot clay.

Data for specimens of buckshot clay consolidated from a slurry were obtained from studies reported by Donaghe and Townsend (1975) and Peters, Leavell and Johnson (1982). These data, which have been tabulated in Appendix IV, were used with the consolidation data obtained during the investigation reported herein to develop an equivalent consolidation relationship. A regression analysis was conducted using void ratio versus applied stress relationships for specimens consolidated from a slurry and for compacted specimens consolidated by applied stresses greater than 16 tsf (1.5 MPa). Mathematically, the equivalent consolidation relationship was expressed as:

$$P_e = P_a \, (e/a)^b \tag{19}$$

where

P_e = equivalent consolidation stress, tsf

P_a = reference consolidation stress, 1 tsf

e = void ratio

a = 1.049

b = -4.497

The consolidation data obtained from slurry specimens along with the equivalent consolidation relationship for buckshot clay have been superimposed on the consolidation data which were reported in Figures 30 through 36 and are presented in Figures 38 through 44, respectively. As may be observed, the equivalent consolidation stress relationship fits the laboratory data well. Furthermore, the equivalent consolidation relationship and the compression indices for selected ranges of void ratio from this relationship are consistent with the results reported by other investigators. For example, Molina (1960) reported a compression index of 0.43 for void ratios ranging from 0.9 to 0.85, as compared to 0.45 for the equivalent consolidation relationship. Donaghe and Townsend (1975) reported a compression index of 0.35 for void ratios ranging from 0.8 to 0.7 as compared to 0.37 for this relationship. Similarly, Peters, Leavell and Johnson (1982) reported a compression index of 0.29 for void ratios ranging from 0.8 to 0.6 as compared to 0.32 for the equivalent consolidation relationship.

Strength Tests

Three series of triaxial compression tests were conducted on Vicksburg buckshot clay to assess the influence of soil suction on the shear strengths of unsaturated soil. To provide a reference to evaluate the strengths of unsaturated clay, 20 consolidated undrained triaxial tests with pore pressure measurements were conducted on back pressure saturated specimens. To assess the influence of matrix suction on the strengths of unsaturated soil, 15 specimens, compacted at a nominal water content of 20 percent, and 16 specimens, compacted at a nominal water content of 26 percent, were tested at the natural water content of the specimens. To assess the influence of solute suction on the strengths of unsaturated soil, 13 specimens were treated with potassium chloride, compacted at nominal water contents of 20 and 26 percent, and tested at natural water content conditions.

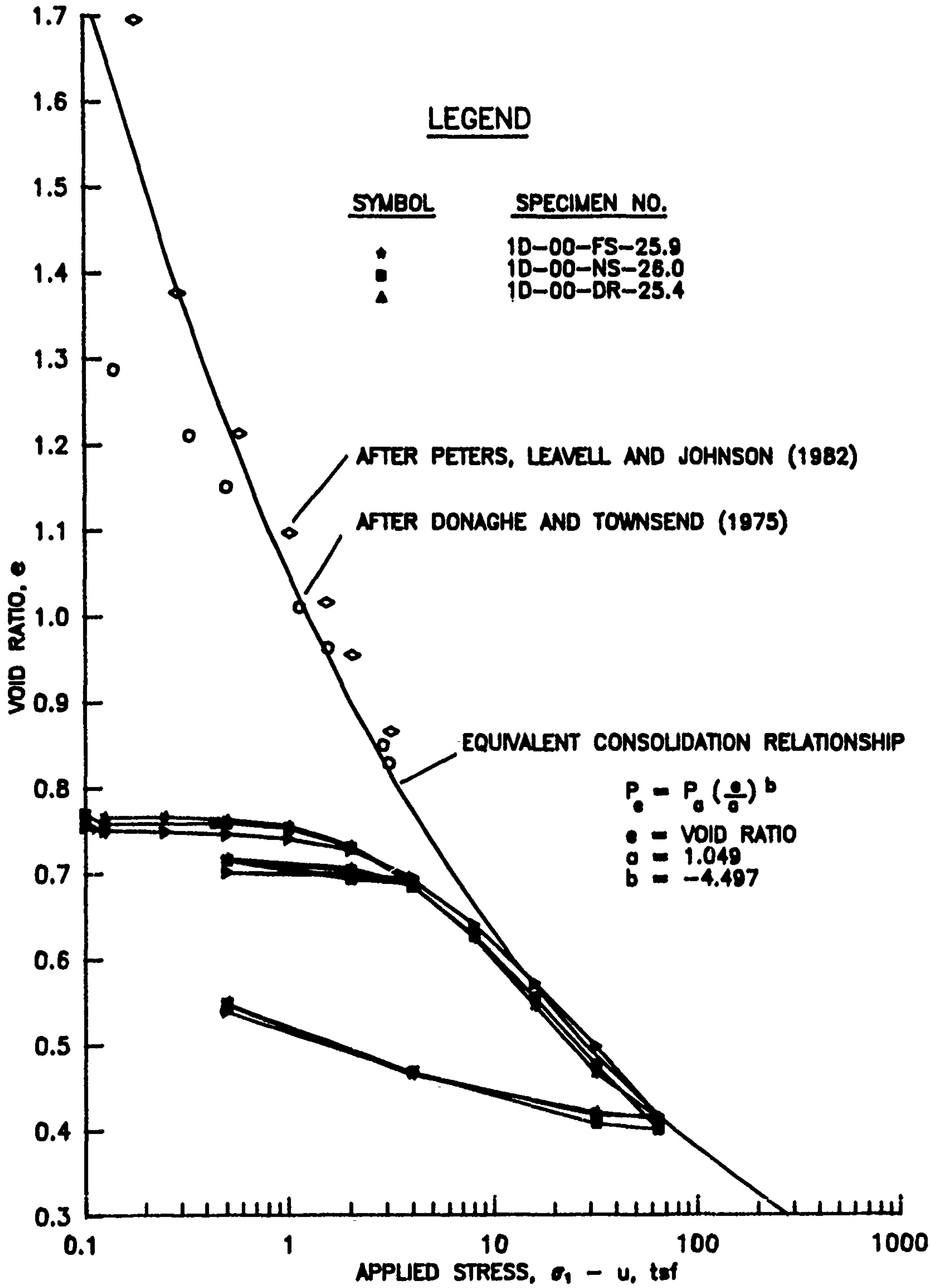

FIG. 38. Equivalent consolidation relationship superimposed on one dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 26 percent. (1 tsf = 96 kPa)

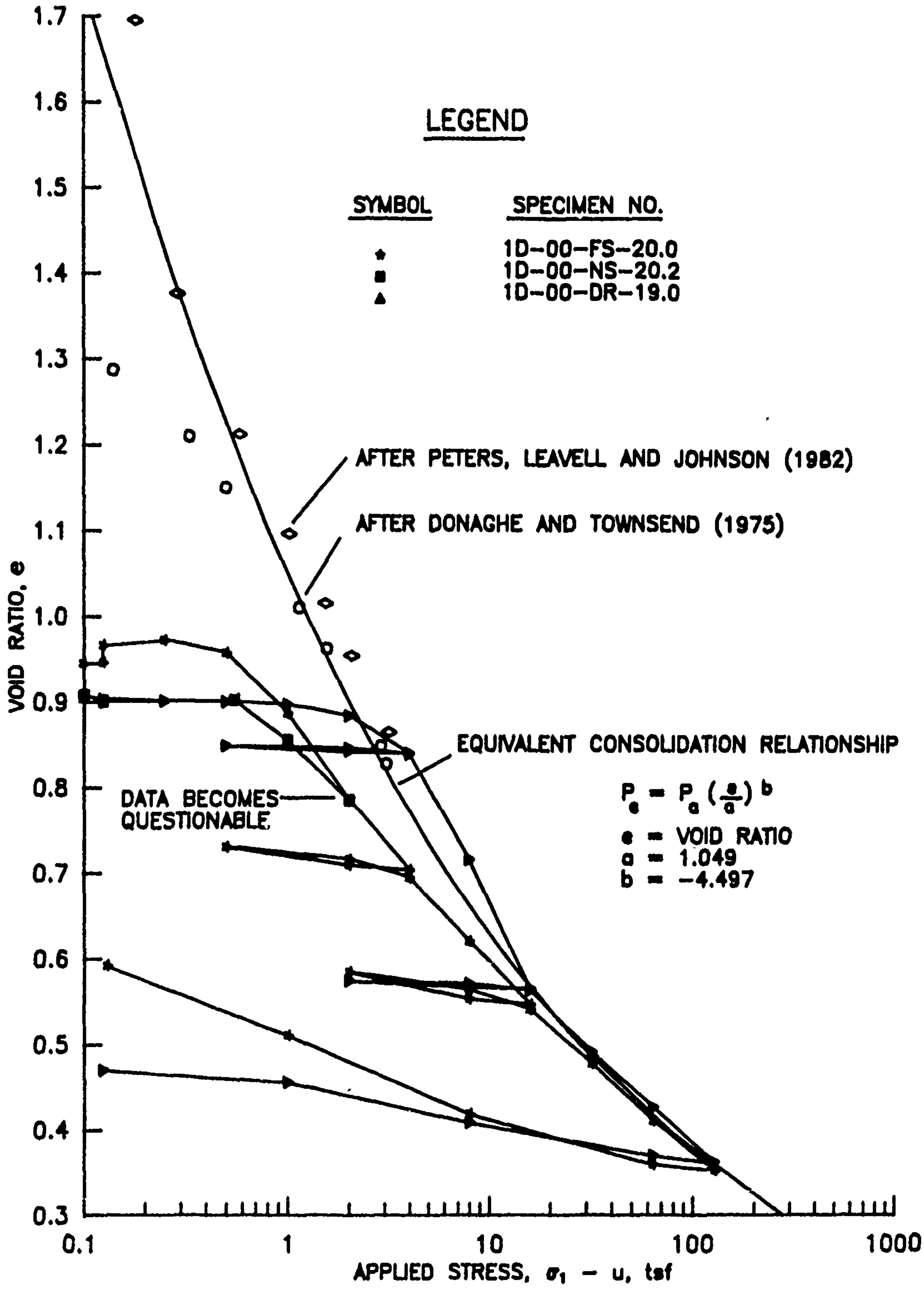

FIG. 39. Equivalent consolidation relationship superimposed on one dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 20 percent. (1 tsf = 96 kPa)

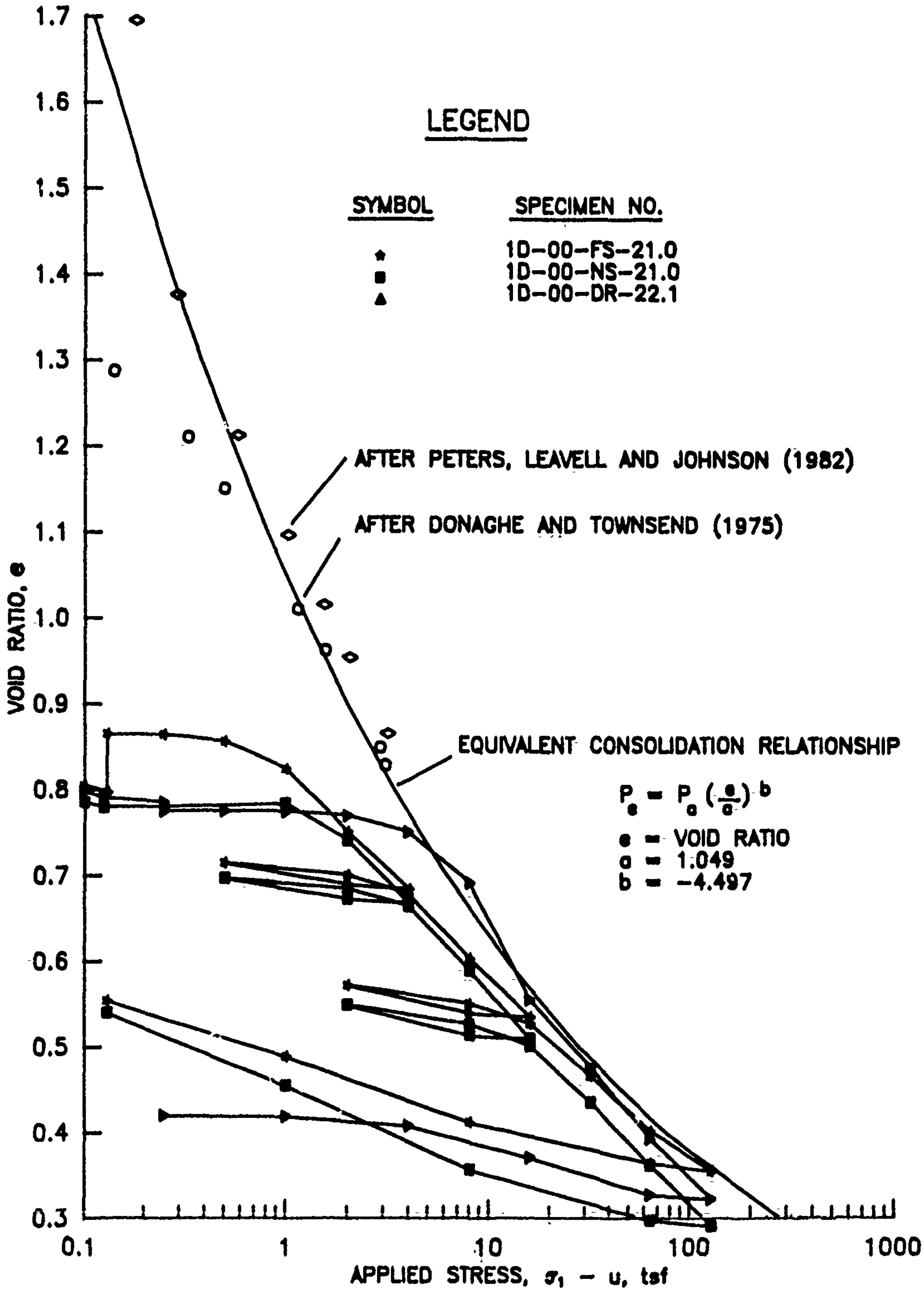

FIG. 40. Equivalent consolidation relationship superimposed on one dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 21 percent. (1 tsf = 96 kPa)

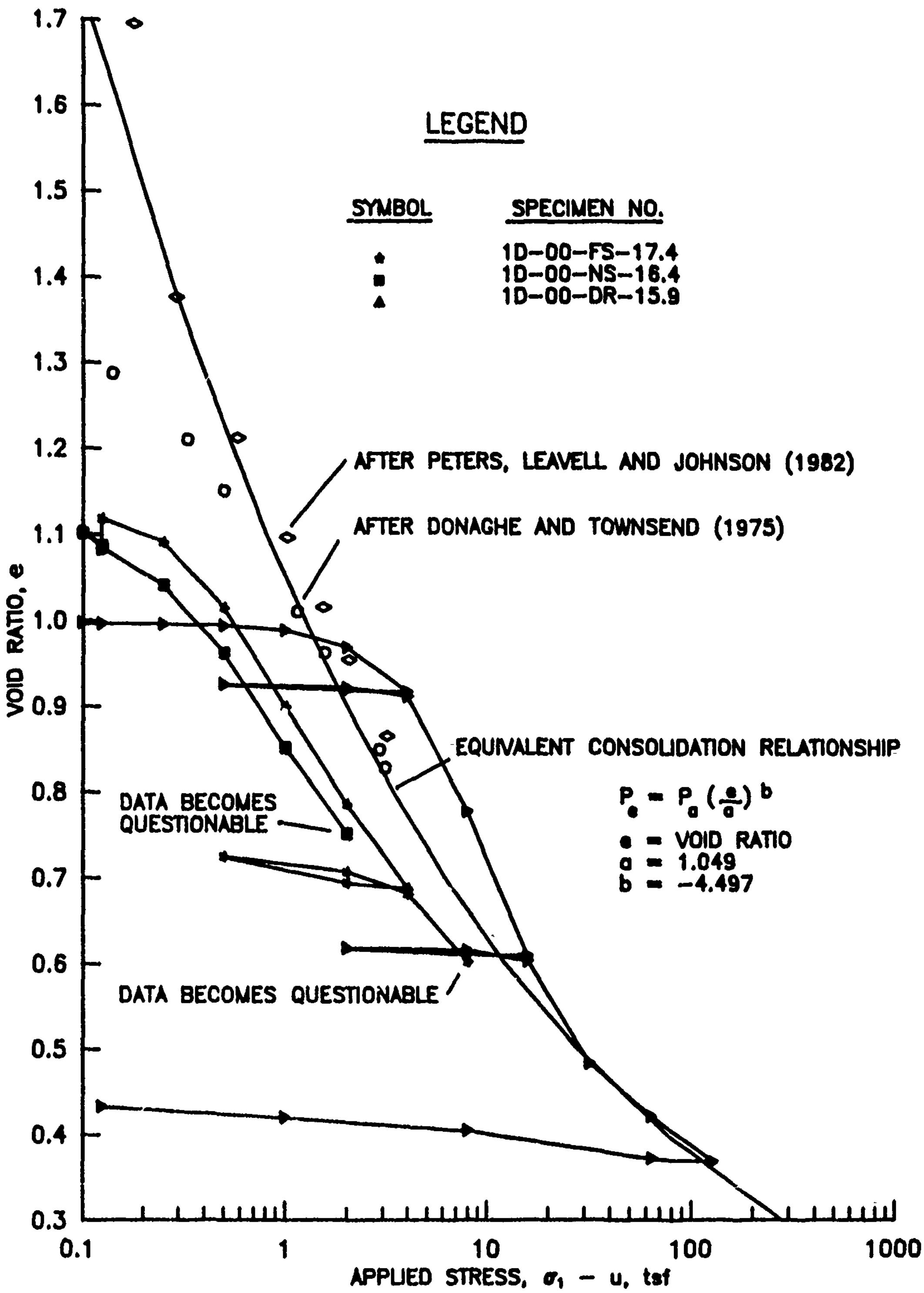

FIG. 41. Equivalent consolidation relationship superimposed on one dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 17 percent. (1 tsf = 96 kPa)

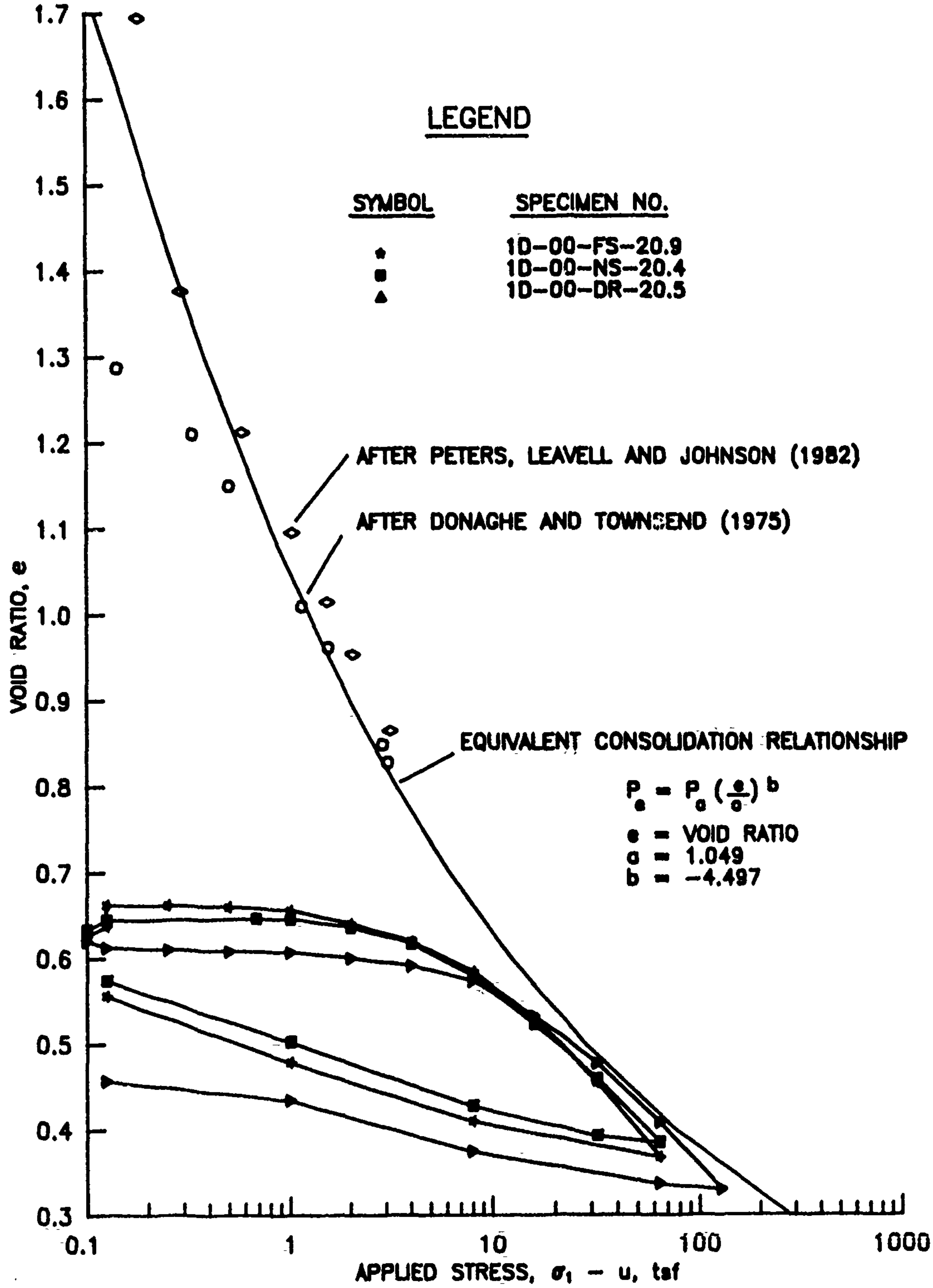

FIG. 42. Equivalent consolidation relationship superimposed on one dimensional consolidation test results for specimens of buckshot clay compacted at a nominal water content of 21 percent using the high compactive effort. (1 tsf = 96 kPa)

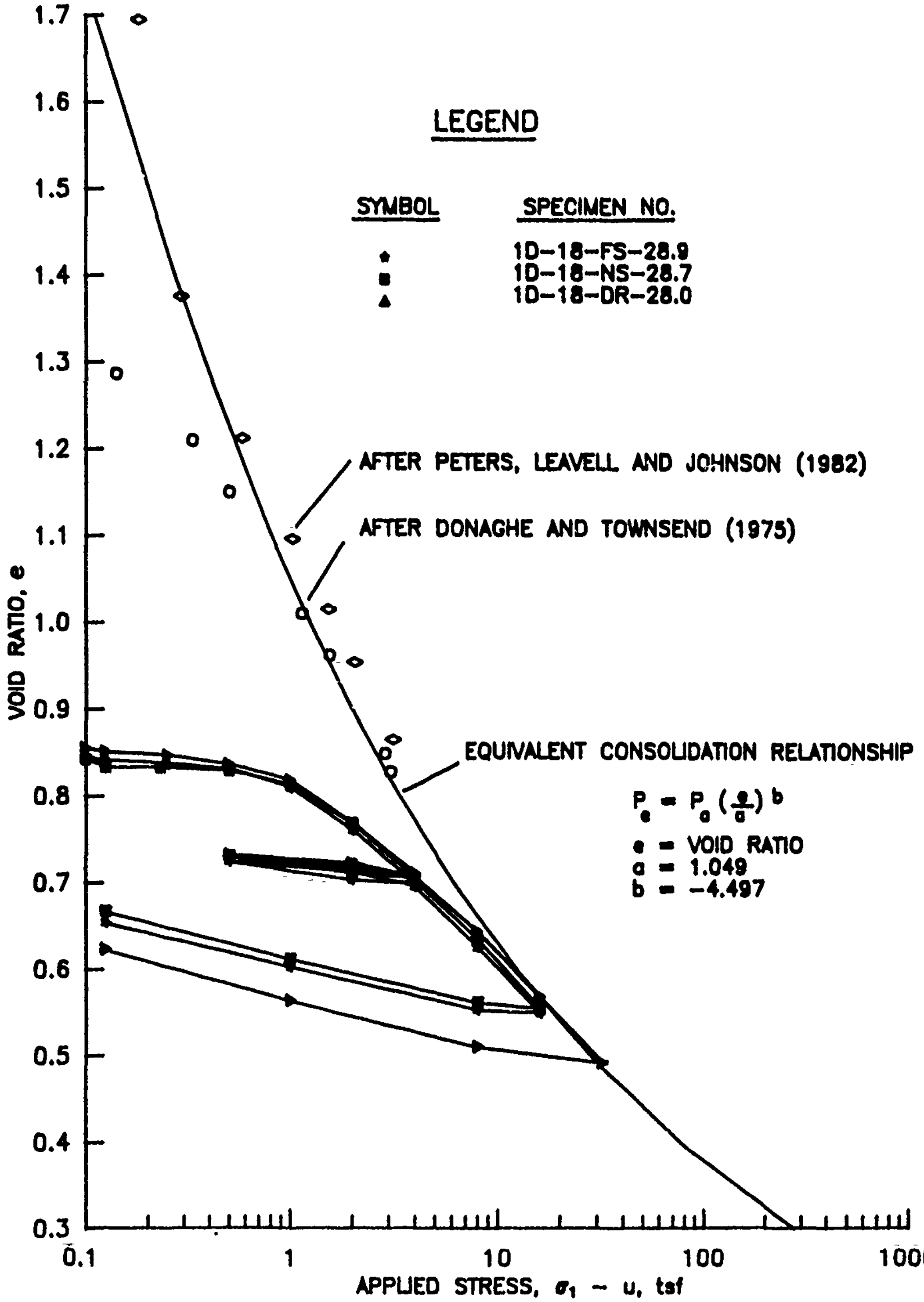

FIG. 43. Equivalent consolidation relationship superimposed on one dimensional consolidation test results for specimens of buckshot clay treated with potassium chloride prior to compaction at a nominal water content of 28 percent. (1 tsf = 96 kPa)

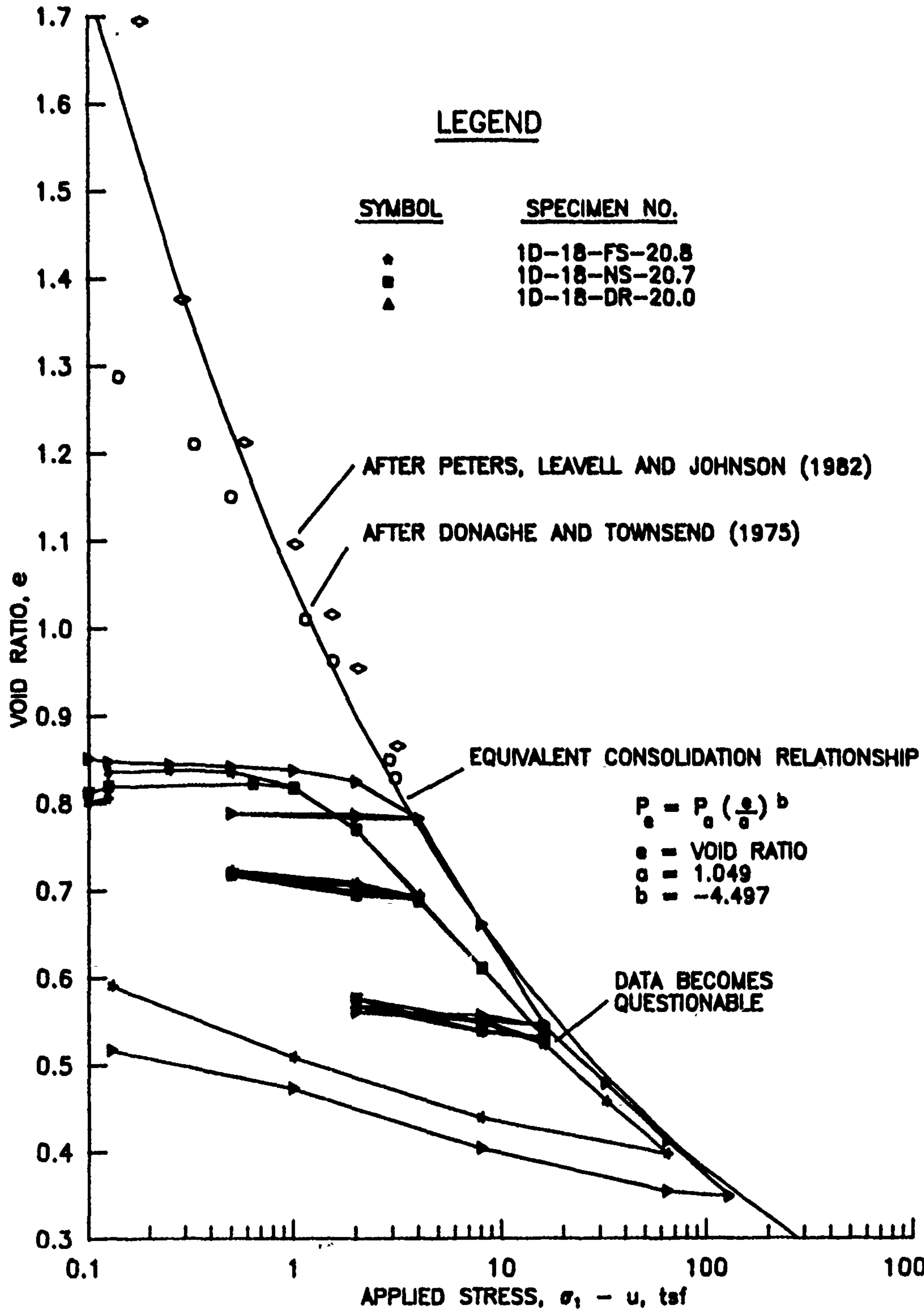

FIG. 44. Equivalent consolidation relationship superimposed on one dimensional consolidation test results for specimens of buckshot clay treated with potassium chloride prior to compaction at a nominal water content of 20 percent. (1 tsf = 96 kPa)

Each specimen was identified using the nomenclature described below. For example, the code for specimen TXS-25-DR-27-160-2(2) was:

"TXS" identified the test as a triaxial shear test

"25" identified the estimated value of solute suction in tons per square foot (tsf) based upon the weight of KCl added to the pore water

"DR" identified the initial boundary conditions imposed upon the test specimen

"27" was the nominal water content of the compacted specimen expressed as a percentage

"160" was the isotropic consolidation pressure expressed as pounds per square inch (psi) (1 psi = 0.07 tsf = 7 kPa)

"2" was analogous to an overconsolidation ratio

"(2)" was the number of the test specimen which was subjected to a particular consolidation and rebound sequence prior to shear.

The term "DR" identified an unsaturated or natural water content test specimen and "FS" identified a free swell test specimen.

Guided by observations that the deformed shape of the triaxial specimens closely resembled a barrel shaped bulge, it was decided that the mathematical calculation of the deformed shape and cross sectional area of each specimen could be based upon the equation for a frustum of a cone. For this calculation, it was assumed that no radial deformation occurred at the top and bottom of the specimen and that maximum deformation occurred at the center of the specimen. The diameter was calculated using Equation 20:

$$D_i = (-D_o + \{D_o^2 - 4[D_o^2 - (12\ V_i)/(\pi\ H_i)]\}^{0.5})/2 \qquad (20)$$

where

D_i = diameter at the center of the deformed specimen at any instant during the test

D_o = initial diameter of the specimen

V_i = volume of the specimen at any instant during the test

H_i = height of the specimen at any instant during the test

For back pressure saturated specimens, the volume remained constant during shear because the specimens were undrained. The height of the specimen at any instant during the test could be determined from the LVDT measurements. For unsaturated specimens, the height and volume of the specimens were related to LVDT measurements and to the volume of water which was expelled from the inner chamber as the test was conducted.

Strength of Saturated Buckshot Clay

The results of consolidated undrained triaxial compression tests with pore pressure measurements are expressed in Figures 45 through 48 as shear stress versus normal stress, where

$$\text{shear stress} = q = [(\sigma_1 - u) - (\sigma_3 - u)]/2 \qquad (21)$$

and

$$\text{normal stress} = p = [(\sigma_1 - u) + (\sigma_3 - u)]/2 \qquad (22)$$

The maximum and minimum principal stresses are $(\sigma_1 - u)$ and $(\sigma_3 - u)$, respectively, and u is the pore water pressure. Using these data, the saturated strength parameters can be determined from the failure envelope:

$$q = a + p \tan \alpha \qquad (23)$$

The slope of the failure surface is $\tan \alpha$ and the intercept is a. Cohesion, c', and the angle of internal friction, ϕ', are related to a and α by the relationships:

$$a = c' \cos \phi' \qquad (24)$$

$$\tan \alpha = \sin \phi' \qquad (25)$$

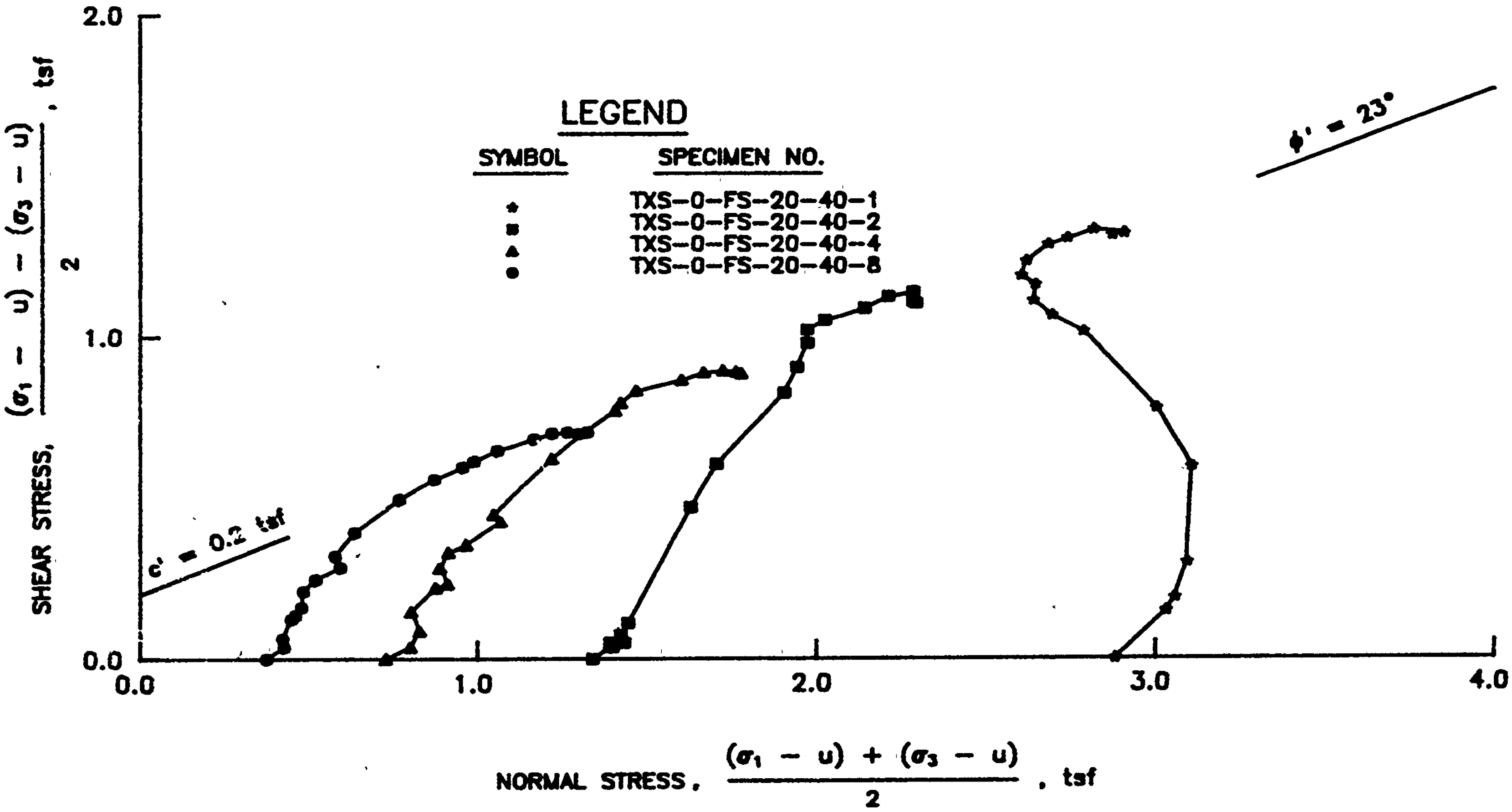

FIG. 45. Shear stress versus normal stress relationships for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 20 percent and consolidated by 2.9 tsf (280 kPa) prior to shear.

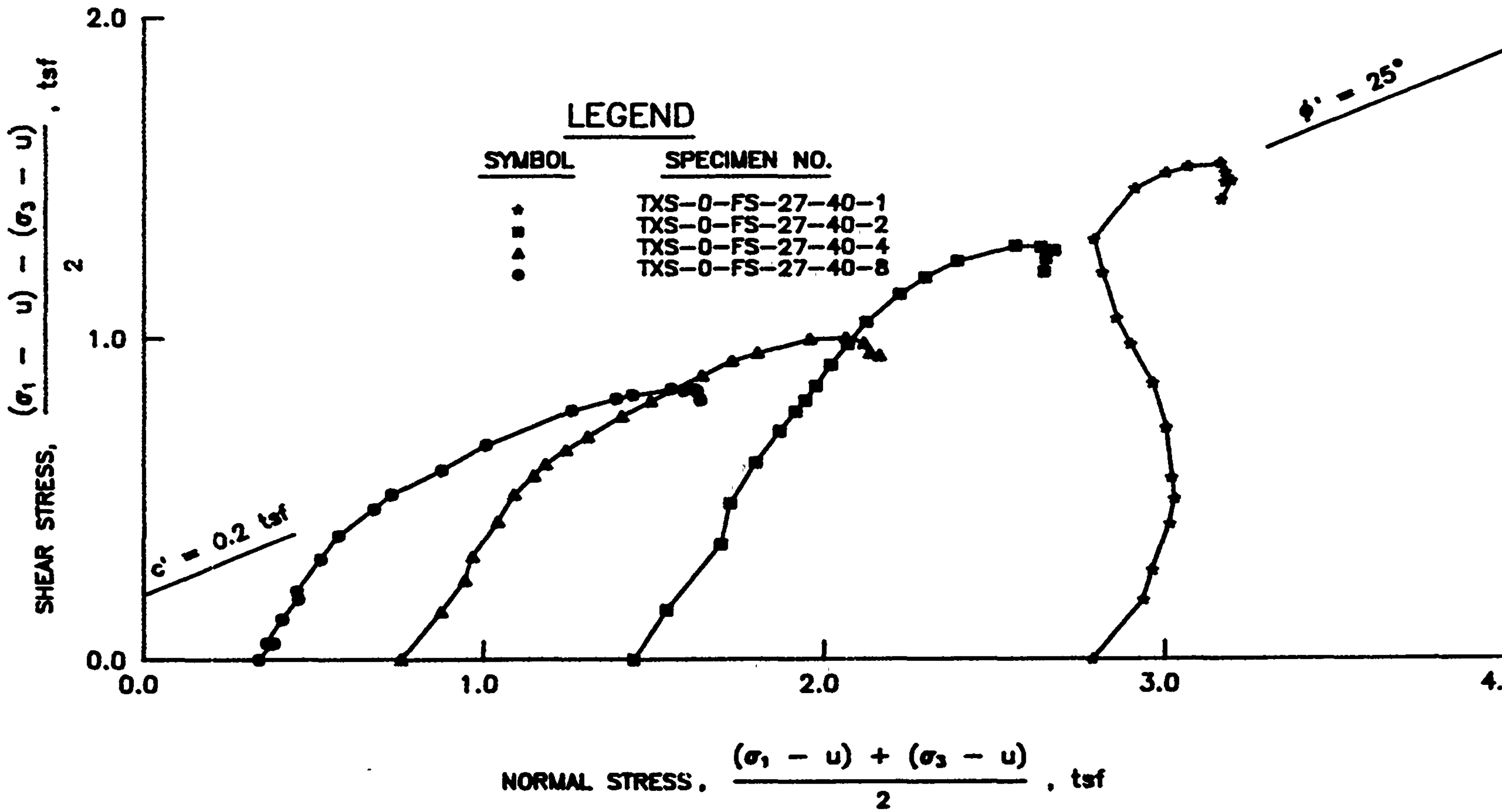

FIG. 46. Shear stress versus normal stress relationships for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 27 percent and consolidated by 2.9 tsf (280 kPa) prior to shear.

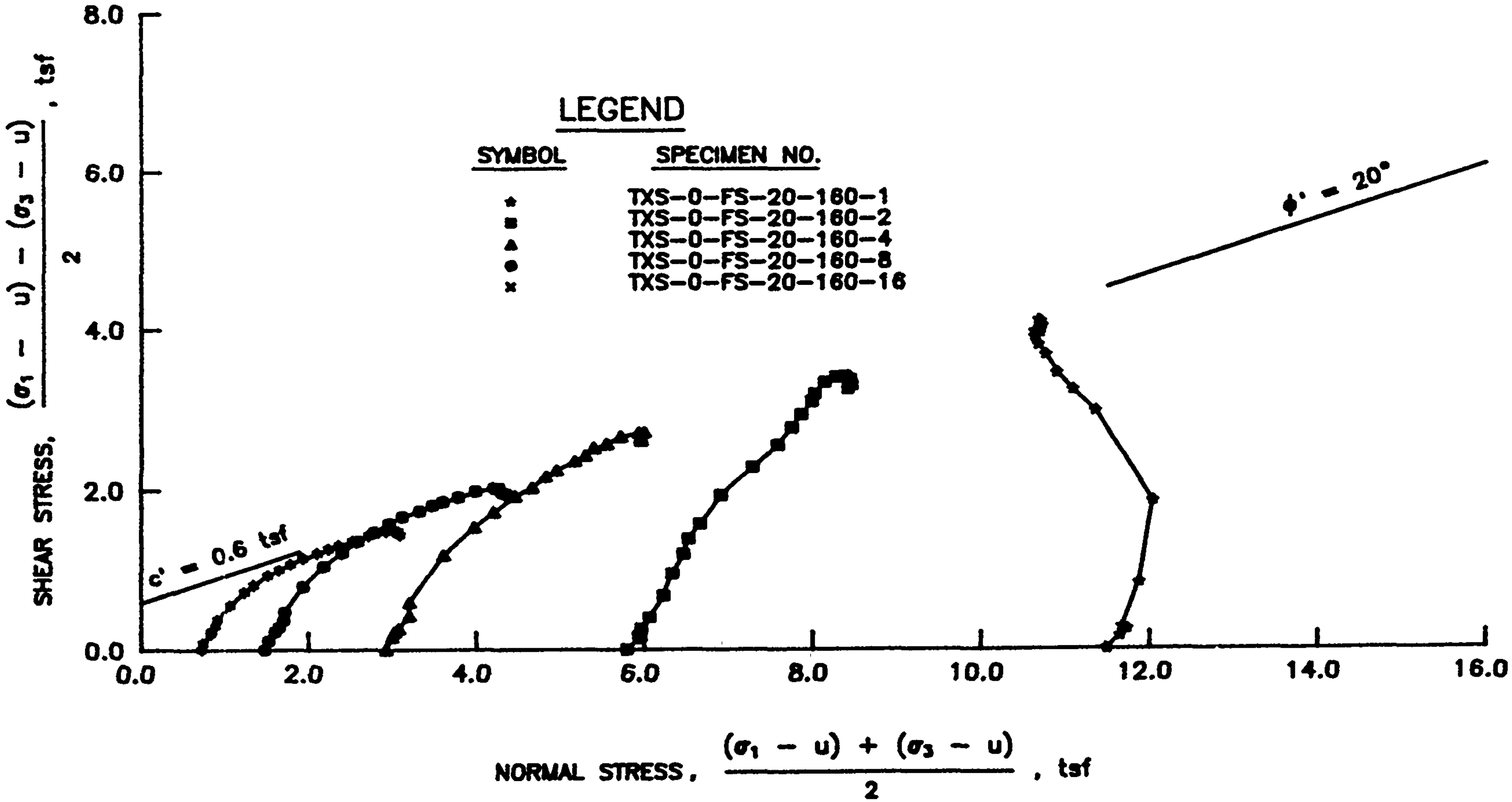

FIG. 47. Shear stress versus normal stress relationships for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 20 percent and consolidated by 11.5 tsf (1.1 MPa) prior to shear.

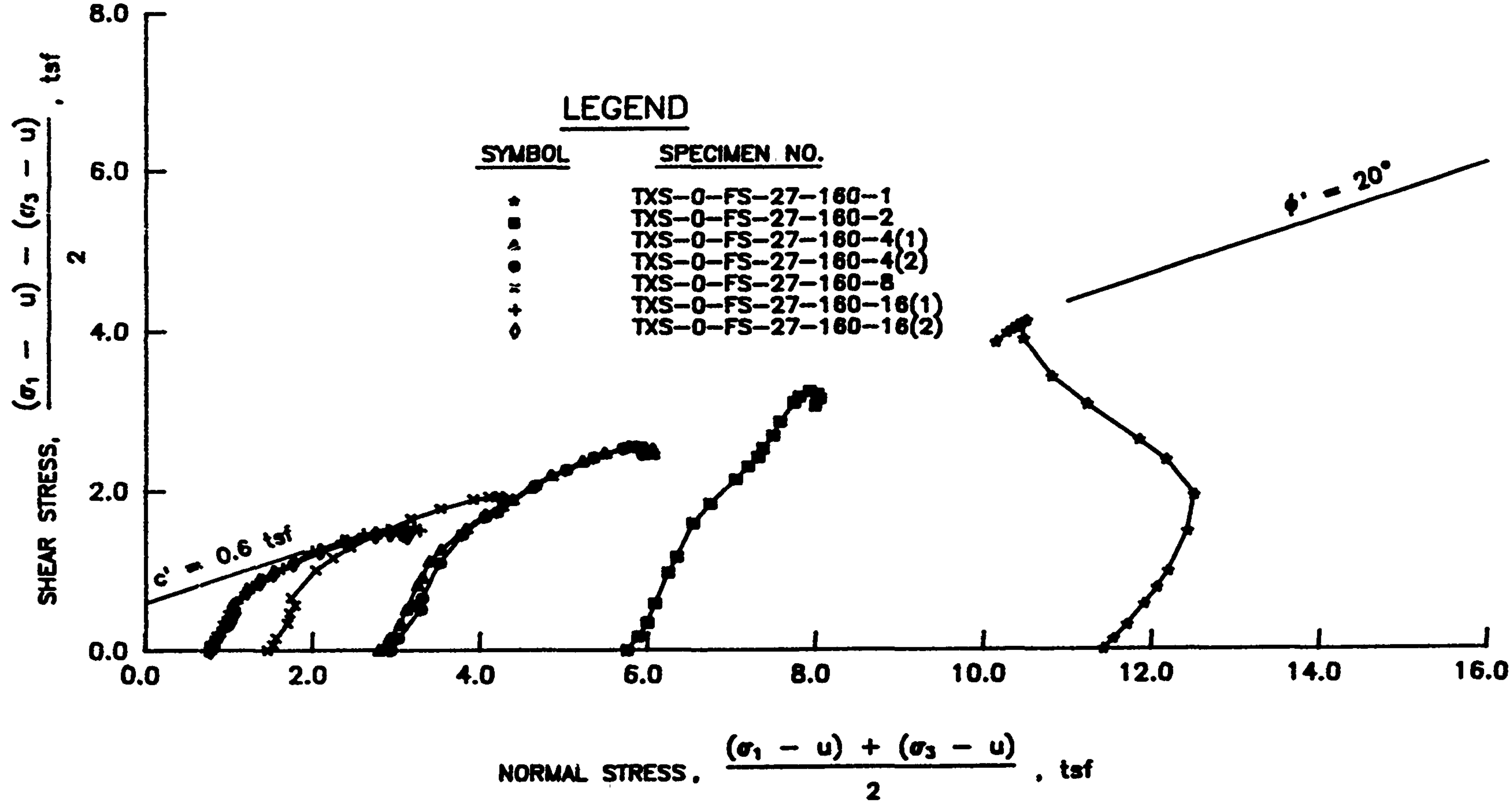

FIG. 48. Shear stress versus normal stress relationships for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 27 percent and consolidated by 11.5 tsf (1.1 MPa) prior to shear.

From the triaxial test results presented in Figures 45 and 46 for specimens compacted at a water content of 20 and 27 percent, respectively, and rebounded from 2.9 tsf (280 kPa) prior to shear, the stress paths indicated that all specimens were overconsolidated and tended to dilate during shear. A "best fit" strength envelope of $c' = 0.2$ tsf (20 kPa) and $\phi' = 23$ deg was determined for specimens compacted at a nominal water content of 20 percent. For specimens compacted at a water content of 27 percent, the strength envelope was $c' = 0.2$ tsf (20 kPa) and $\phi' = 25$ deg. The results of tests on specimens compacted at water contents of 20 and 27 percent and rebounded from 11.5 tsf (1.1 MPa) prior to shear are presented in Figures 47 and 48, respectively. Stress path data indicated these specimens were overconsolidated and tended to dilate during shear. Strength envelopes of $c' = 0.6$ tsf (60 kPa) and $\phi' = 20$ deg were determined for these tests. The differences of strength parameters for specimens rebounded from 2.9 and 11.5 tsf (280 kPa and 1.1 MPa) were likely due to differences of specimen densities. Void ratios ranged from 0.55 to 0.66 for specimens rebounded from 11.5 tsf (1.1 MPa) as compared to void ratios ranging from 0.67 to 0.75 for specimens rebounded from 2.9 tsf (280 kPa).

Based upon test results reported in the literature, the shear strengths for the tests reported herein appeared to be reasonable. Donaghe and Townsend (1975) reported an angle of internal friction of approximately 23 deg and a cohesion intercept of 0.2 tsf (20 kPa) for specimens prepared from a slurry and consolidated by a maximum stress of 6.1 tsf (580 kPa) prior to shear. However, Donaghe and Townsend's specimens were less dense and less overconsolidated than the specimens for the current investigation, perhaps as a result of the specimen preparation procedures. The void ratios of Donaghe and Townsend's specimens ranged from 0.86 to 0.65 for consolidation stresses ranging from 1.5 to 6.1 tsf (140 to 580 kPa) as compared to void ratios from 0.75 to 0.55 for the investigation reported herein. Molina (1960) reported an angle of internal friction of 19 deg and a cohesion intercept of 0.4 tsf (40 kPa) for specimens prepared from a slurry and consolidated by stresses as large as 8 tsf (770 kPa). Although the angle of

friction reported by Molina was less than the angles of friction reported by Donaghe and Townsend or for the current study, Molina's specimens were less dense than the specimens tested at WES. The void ratios of Molina's specimens ranged from 1.49 before consolidation to 0.8 after consolidation.

To minimize the effects of density differences, results of the strength tests were normalized by an equivalent consolidation relationship similar to the procedure suggested by Bishop and Henkel (1962). Substituting Equations 24 and 25 into 23 and rearranging terms yielded:

$$q = \left[\frac{(\sigma_1 - u) - (\sigma_3 - u)}{2}\right]$$

$$= \left[c' \frac{\cos \phi'}{1 + \sin \phi'} + (\sigma_1 - u) \frac{\sin \phi'}{1 + \sin \phi'}\right] \tag{26}$$

Each stress variable in Equation 26 was divided by the equivalent consolidation stress, P_e, to obtain the normalized strength relationship:

$$\frac{q}{P_e} = \left[\frac{(\sigma_1 - u) - (\sigma_3 - u)}{2\ P_e}\right]$$

$$= \left[\frac{C_e}{P_e} \frac{\cos \phi_e}{1 + \sin \phi_e} + \frac{(\sigma_1 - u)}{P_e} \frac{\sin \phi_e}{1 + \sin \phi_e}\right] \tag{27}$$

The test results for saturated specimens were normalized for density variations and are presented in Figures 49 through 52. With the exception of the test results for specimen TXS-0-FS-20-160-1, all specimens defined a strength envelope which appeared to be independent of compaction water content and density differences. A least-squares regression analysis yielded the following normalized strength parameters:

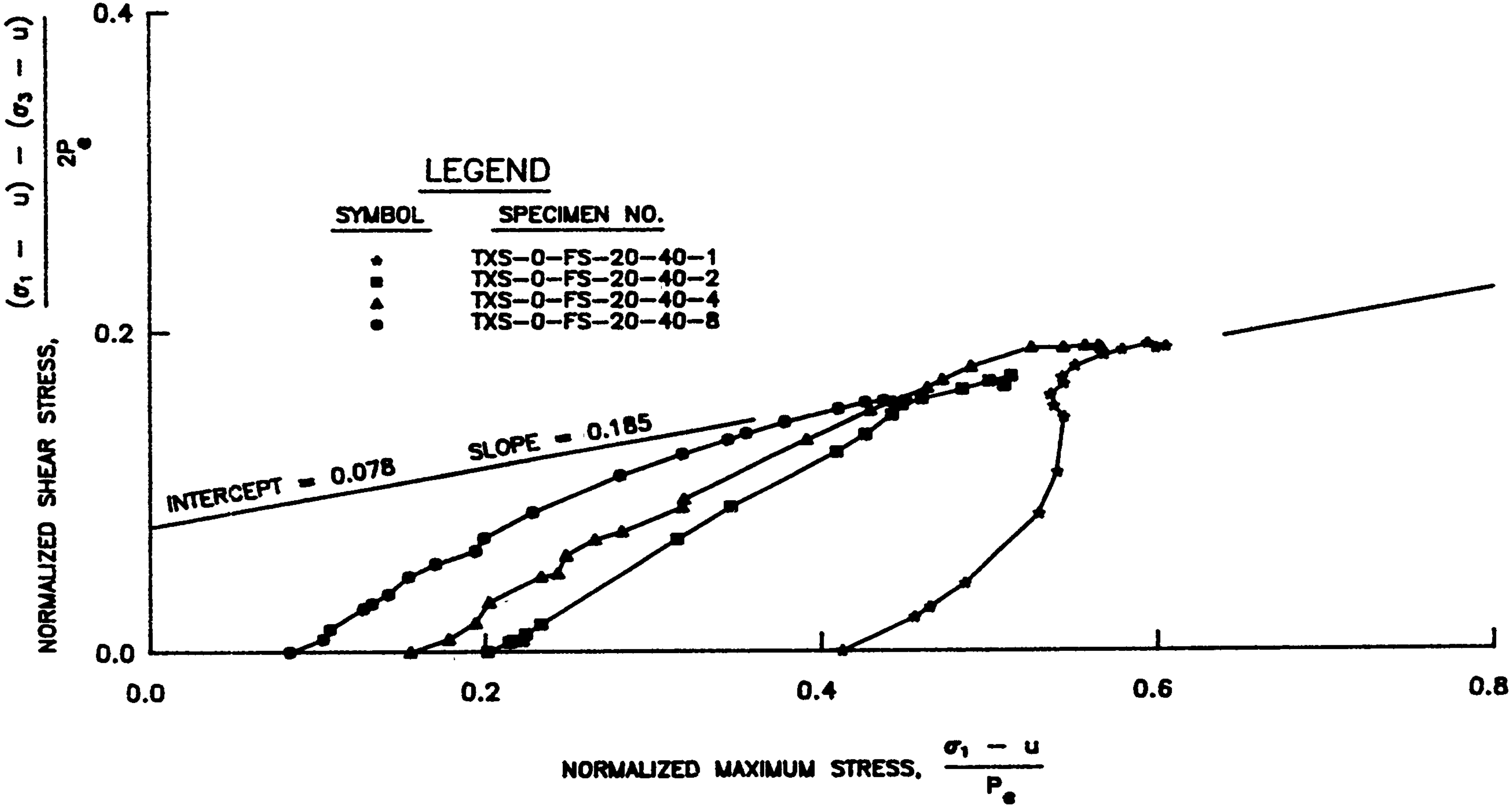

FIG. 49. Normalized stress path relationships for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 20 percent and consolidated by 2.9 tsf (280 kPa) prior to shear.

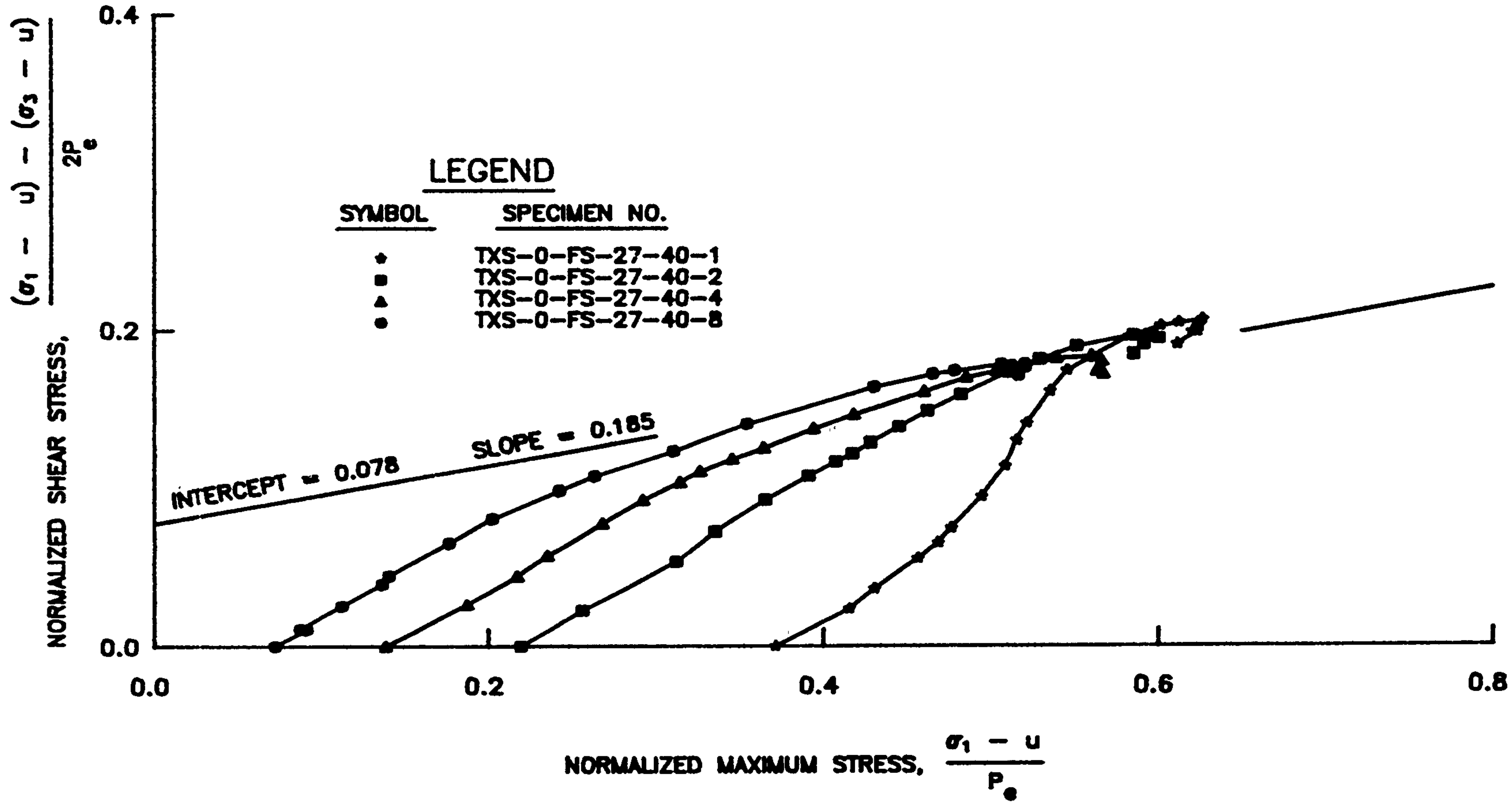

FIG. 50. Normalized stress path relationships for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 27 percent and consolidated by 2.9 tsf (280 kPa) prior to shear.

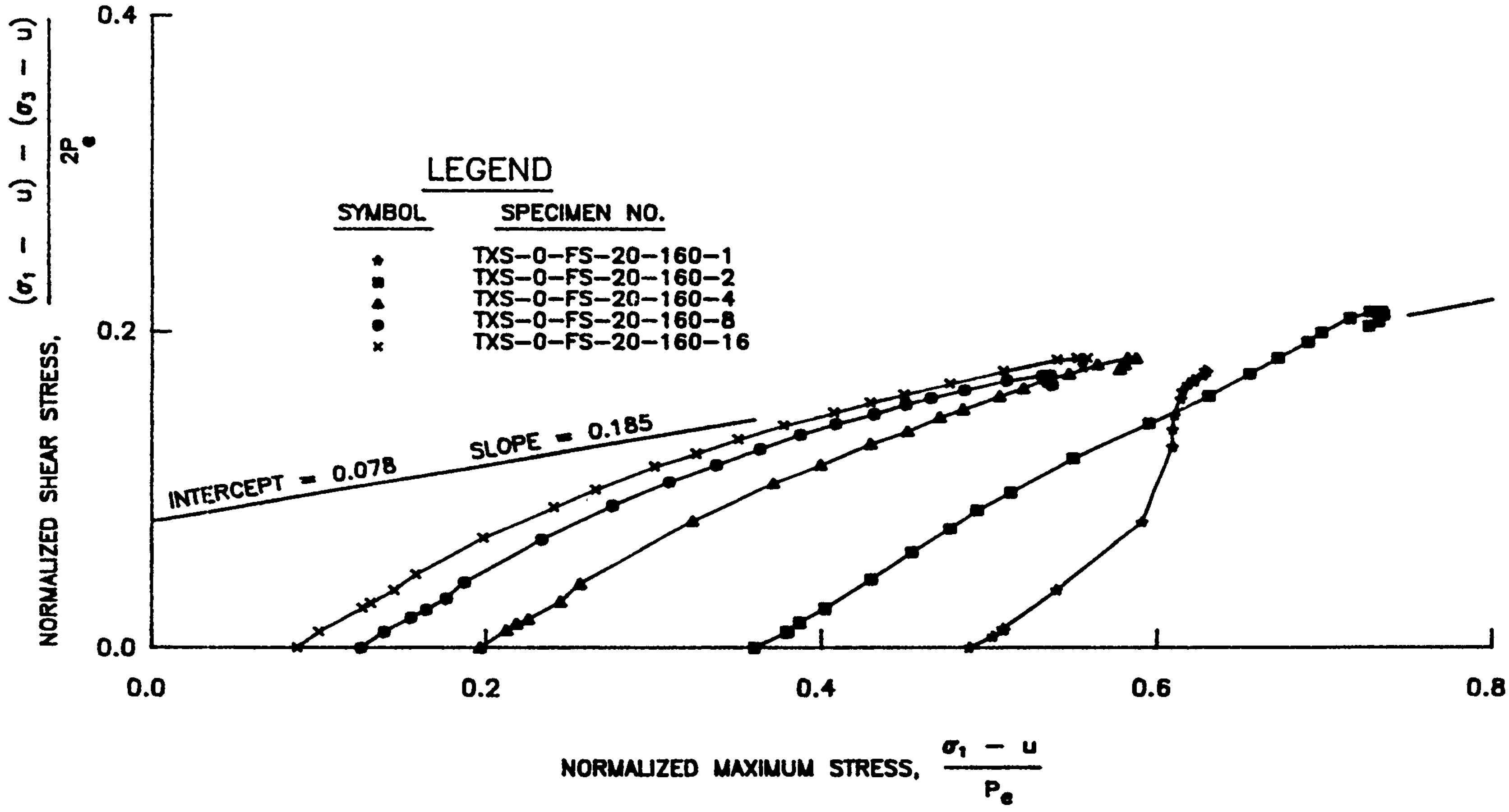

FIG. 51. Normalized stress path relationships for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 20 percent and consolidated by 11.5 tsf (1.1 MPa) prior to shear.

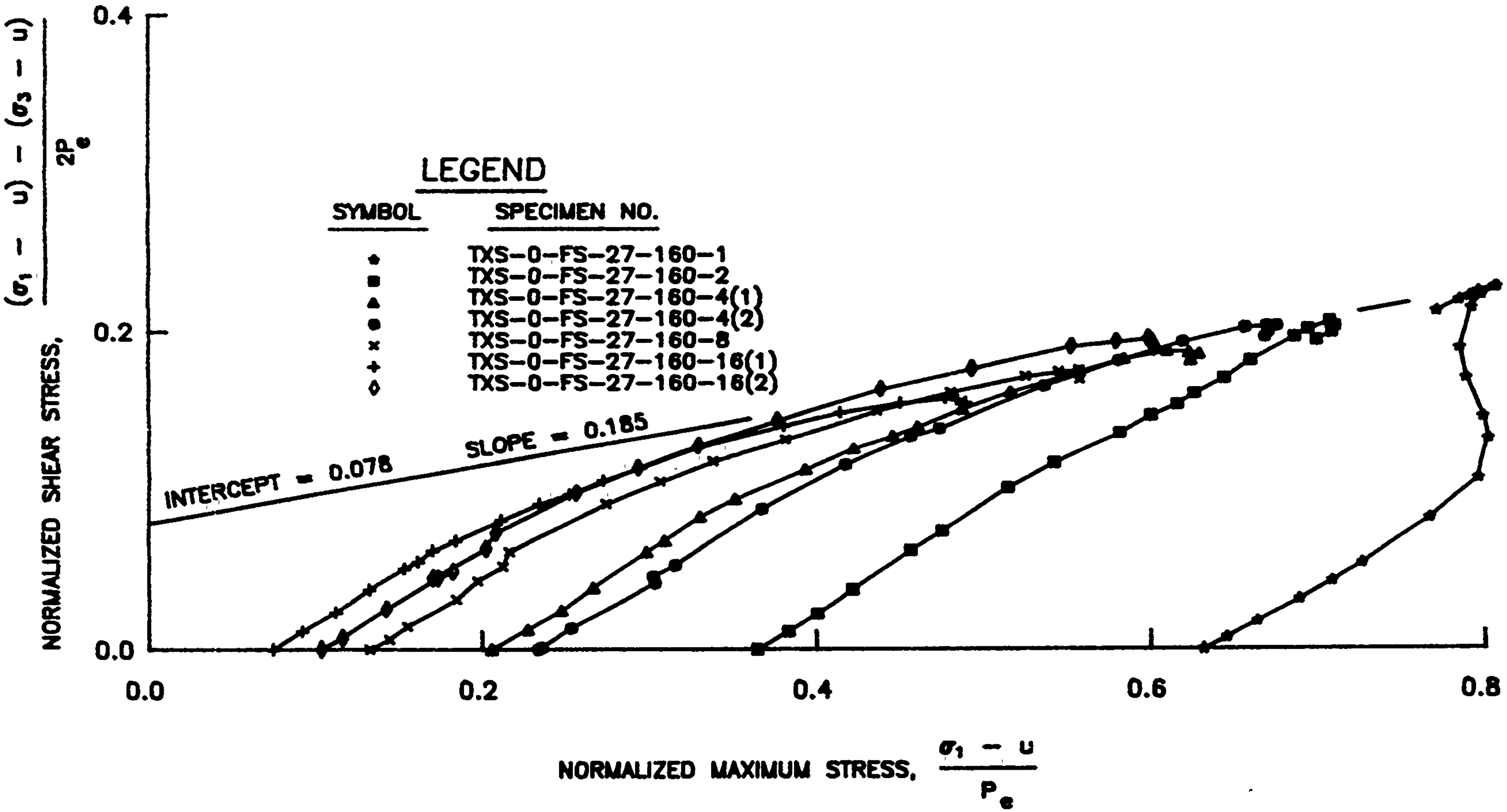

FIG. 52. Normalized stress path relationships for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 27 percent and consolidated by 11.5 tsf (1.1 MPa) prior to shear.

$$\text{slope} = \frac{\sin \phi_e}{1 + \sin \phi_e} = 0.185 \tag{28}$$

$$\text{intercept} = \frac{C_e}{P_e} \frac{\cos \phi_e}{1 + \sin \phi_e} = 0.078 \tag{29}$$

$$\text{correlation coefficient, } r = 0.948 \tag{30}$$

$$\phi_e = 13 \text{ deg} \tag{31}$$

$$C_e/P_e = 0.10 \tag{32}$$

These normalized strength parameters provided a reference to evaluate the shear strengths of unsaturated specimens.

The values of true friction and true cohesion appeared to be reasonable based upon Molina's (1960) data. Molina reported values for true friction, ϕ_e, of 16 degrees and true cohesion, C_e/P_e, of 0.08. Differences between Molina's data and the results for this investigation are likely due to differences of the equivalent consolidation stress and the way it was calculated. Donaghe and Townsend's (1975) data were also reanalyzed using the proposed equivalent consolidation relationship. Unfortunately, the normalized strength data grouped together and a regression analysis was inappropriate.

Because of potential differences of density between saturated and unsaturated specimens and the difficulty of using normalized strength parameters in geotechnical engineering practice, a method was needed to compare the normalized shear strengths for unsaturated and saturated specimens and to express the results in a form amenable to Mohr-Coulomb failure criteria. After consideration of these requirements, it was decided that the normalized strength of an unsaturated specimen should be compared to the normalized strength of a hypothetical saturated specimen calculated from the strength parameters given by Equations 28 and 29. The comparison should be made at the actual values of the normalized stress, $[(\sigma_1 - u)/P_e]$, and the equivalent consolidation

stress, P_e, for the unsaturated specimen. The differences, if any, could then be attributed to suction.

To validate the procedure, the shear strengths of saturated specimens were compared to the strength of an idealized specimen calculated from the strength parameters given as Equations 28 and 29. Differences of the measured and calculated shear strengths were expressed as the apparent error of the calculated shear strength, q_{error}, as:

$$q_{error} = P_e \left[\left[\frac{(\sigma_1 - u) - (\sigma_3 - u)}{2 P_e} \right]_{saturated} - \left[\frac{C_e}{P_e} \frac{\cos \phi_e}{1 + \sin \phi_e} + \frac{(\sigma_1 - u)}{P_e} \frac{\sin \phi_e}{1 + \sin \phi_e} \right]_{calculated} \right] \tag{33}$$

where

$(\sigma_1 - u)/P_e$ = normalized stress for the specimen at any instant during the test

P_e = equivalent consolidation stress for the specimen at any instant during the test

The results of these calculations are presented in Figures 53 through 56 as the apparent error of the calculated shear strength, q_{error}, versus axial strain. With the exception of the results for specimen TXS-0-FS-20-160-1, values of q_{error} were less than 0.1 tsf (10 kPa) for axial strains ranging from 7 to 17 percent. These calculations revealed that differences between the hypothetical and measured shear strengths for saturated specimens were small, which is consistent with the coefficient of correlation reported as Equation 30.

<u>Strength of Unsaturated Buckshot Clay</u>

Results of constant water content triaxial tests on unsaturated specimens compacted at a water content of 20 percent, consolidated by an isotropic stress of 11.5 tsf (1.1 MPa) and rebounded against 0.7, 1.4, 2.9, 5.8 or 11.5 tsf (70, 140, 280, 550 or 1100 kPa) are presented in Figure 57. The results are expressed as shear stress versus normal

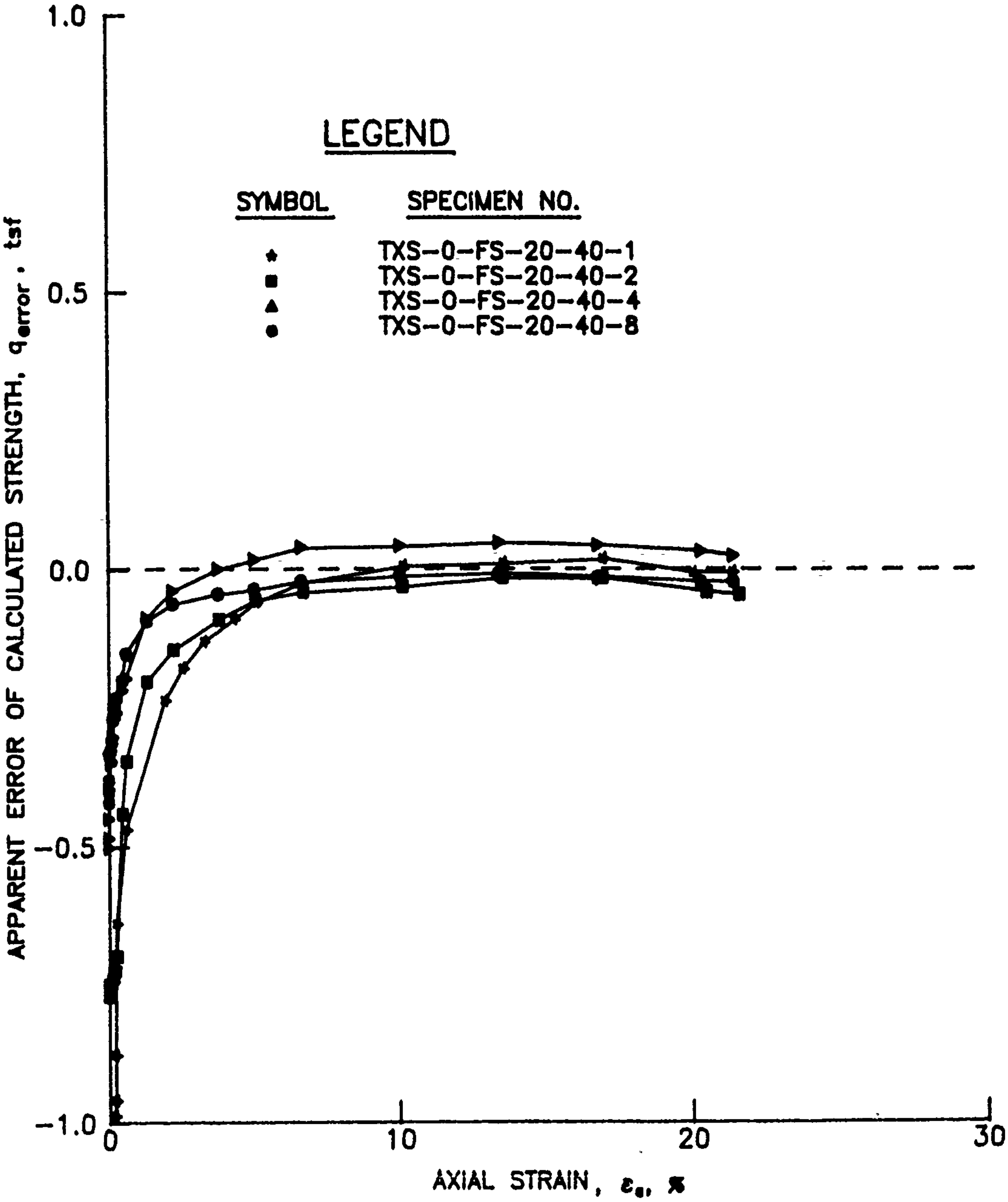

FIG. 53. Differences of measured and calculated shear strengths for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 20 percent and consolidated by 2.9 tsf (280 kPa) prior to shear.

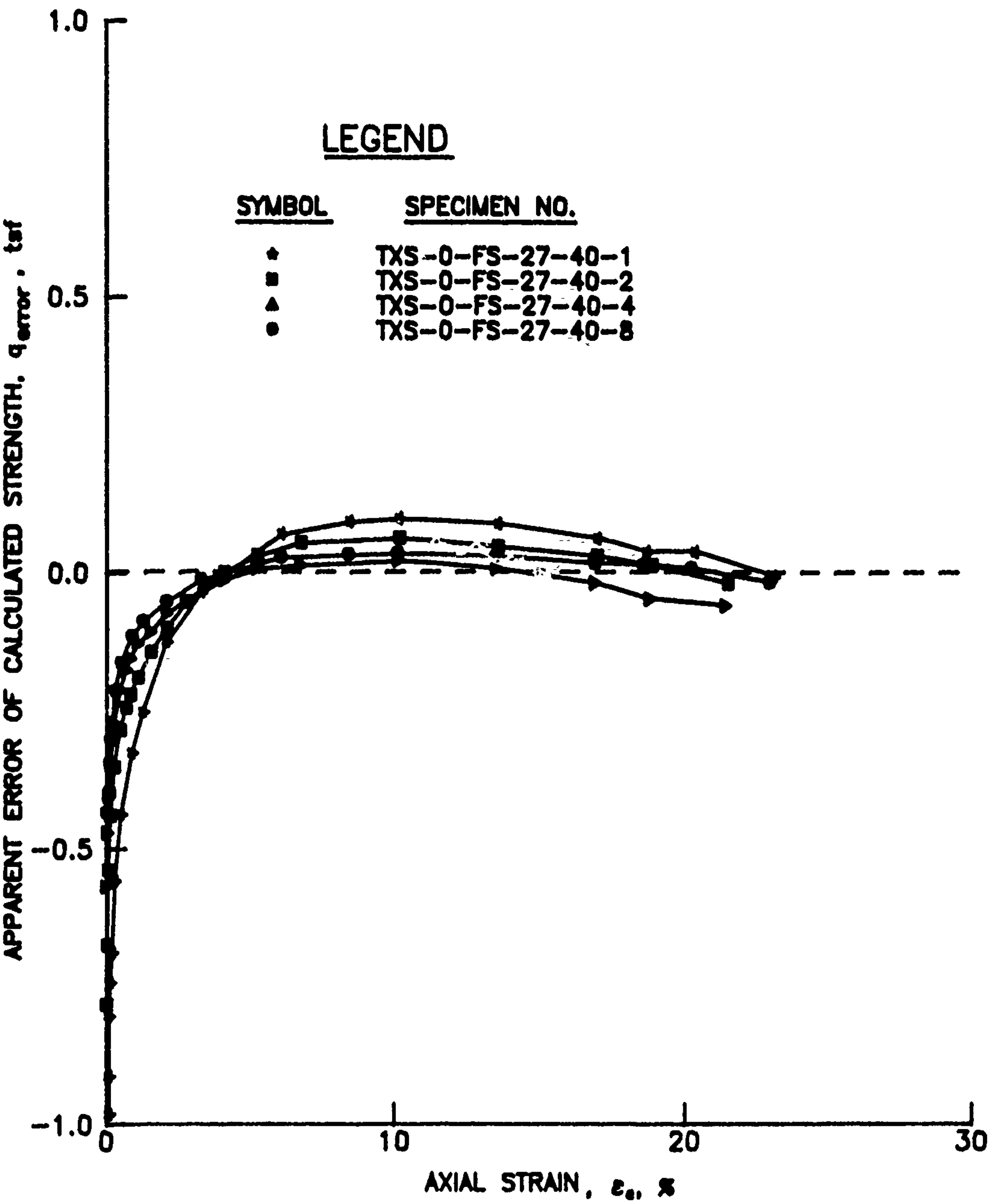

FIG. 54. Differences of measured and calculated shear strengths for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 27 percent and consolidated by 2.9 tsf (280 kPa) prior to shear.

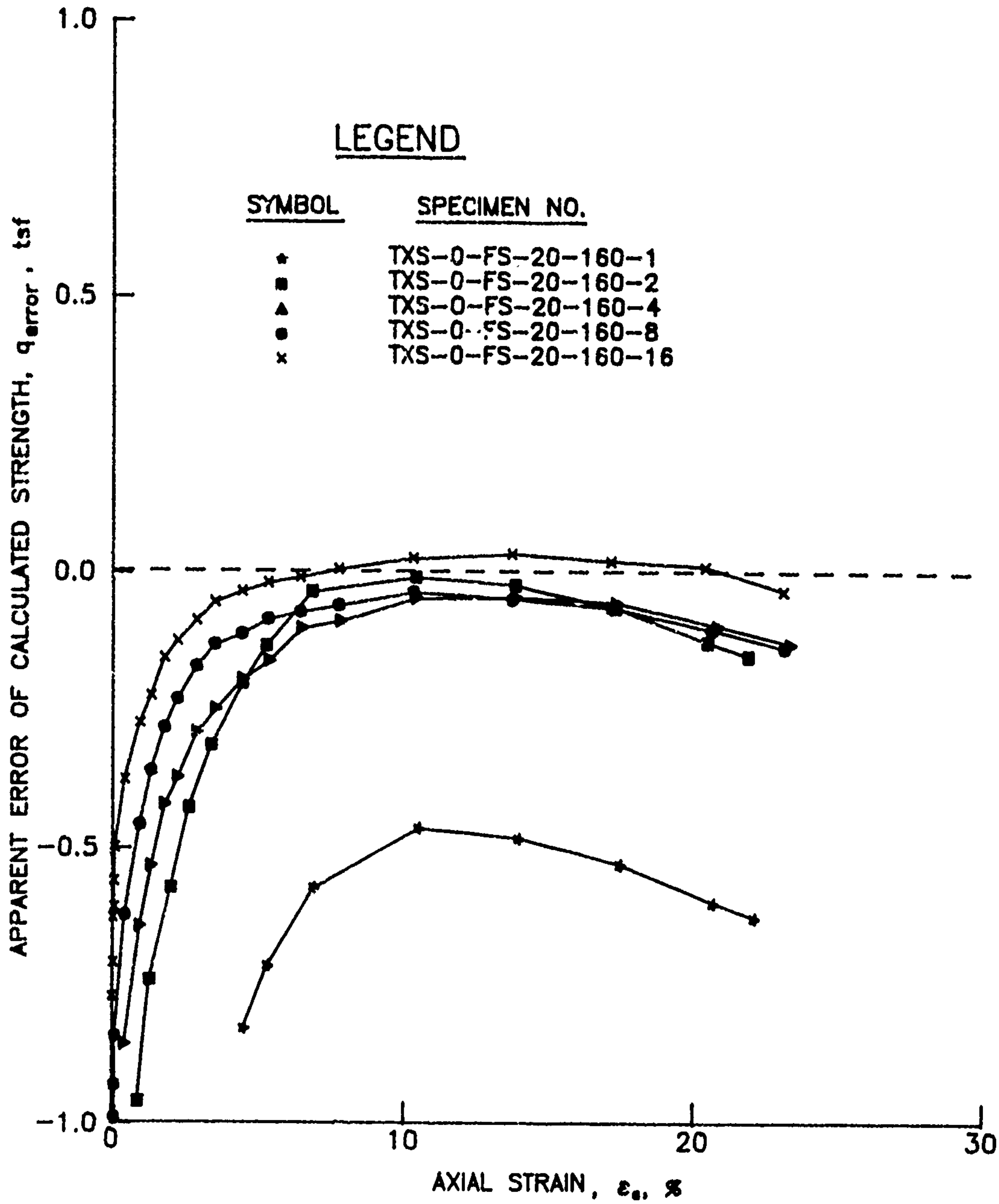

FIG. 55. Differences of measured and calculated shear strengths for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 20 percent and consolidated by 11.5 tsf (1.1 MPa) prior to shear.

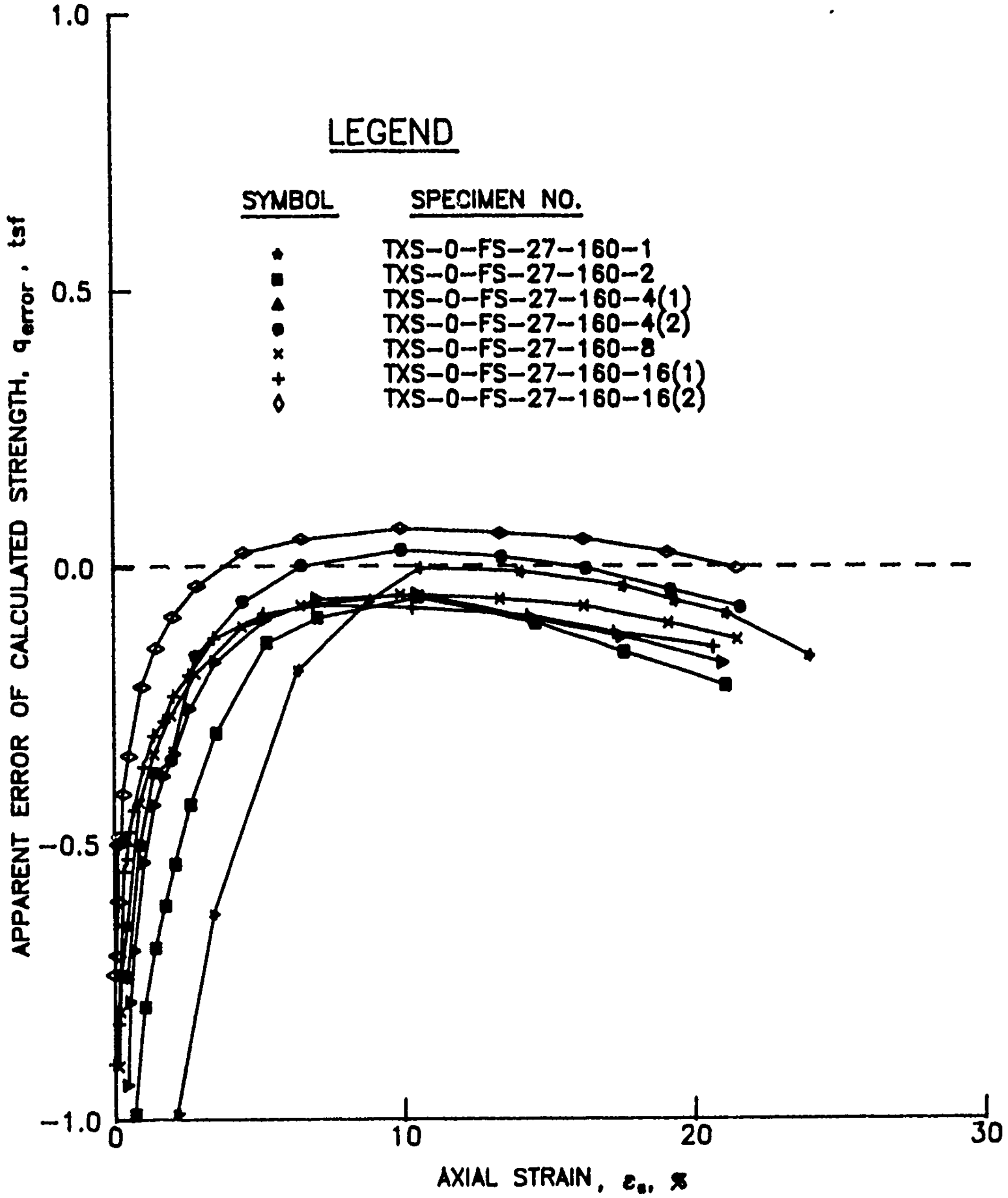

FIG. 56. Differences of measured and calculated shear strengths for back pressure saturated specimens of buckshot clay compacted at a nominal water content of 27 percent and consolidated by 11.5 tsf (1.1 MPa) prior to shear.

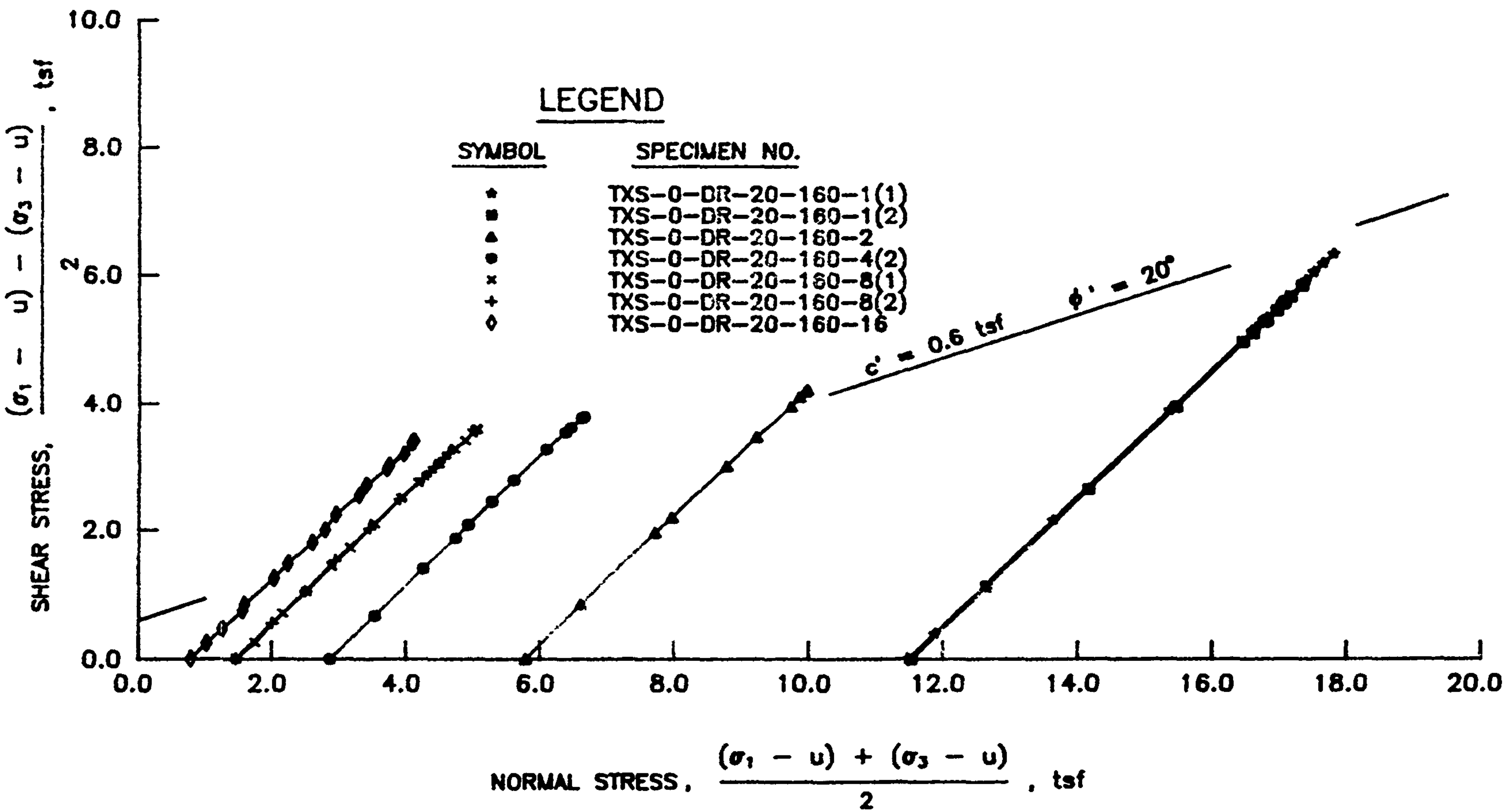

FIG. 57. *Shear stress versus normal stress relationships for compacted specimens of buckshot clay consolidated by 11.5 tsf (1.1 MPa) and sheared at a nominal water content of 20 percent.*

stress, where u is the pore air pressure. Although pore air pressures were not measured during these tests, the pore pressures were assumed to be zero because the tests were conducted slowly and the induced pressures were allowed to dissipate. As inferred by the strength envelope for saturated specimens which has been superimposed on these data, the shear strengths of the unsaturated specimens were usually greater than the shear strengths of saturated specimens. One may also observe from these data that the stress paths increased at a slope of 1, which is identical to the slope of a stress path for a consolidated drained test conducted on a saturated specimen. Unfortunately, these results did little to assist in the assessment of the influence of suction on the shear strength of unsaturated soil because the effects of density and suction could not be separated and evaluated when the data were expressed in this form.

The strengths of unsaturated specimens which were compacted at water contents of 20 and 26 percent are presented in Figures 58 and 59, respectively, as shear strength at failure versus normal stress. The strength envelope determined for saturated specimens rebounded from 11.5 tsf (1.1 MPa) prior to shear has been superimposed on these data. As can be observed from the results presented in Figure 58, the strengths of unsaturated specimens compacted at a water content of 20 percent were generally greater than the strengths of saturated specimens. For specimens which were compacted at a water content of 26 percent, the shear strengths were similar to the strengths of saturated specimens, as can be seen from the data presented in Figure 59. Based upon the test results for unsaturated specimens which have been presented in Figures 57 through 59, it was concluded these data offered little assistance for analysis because independent assessments of the effects of density and suction could not be made.

Test results for unsaturated specimens compacted at a water content of 20 percent were normalized for density variations using Equation 27, where u is the pore air pressure. The normalized shear strengths for specimens sheared at stress states of 0.7, 1.4, 2.9, 5.8 or 11.5 tsf (70, 140, 280, 550 or 1100 kPa) are presented in Figures 60 through 64, respectively. Regression analyses were conducted on the

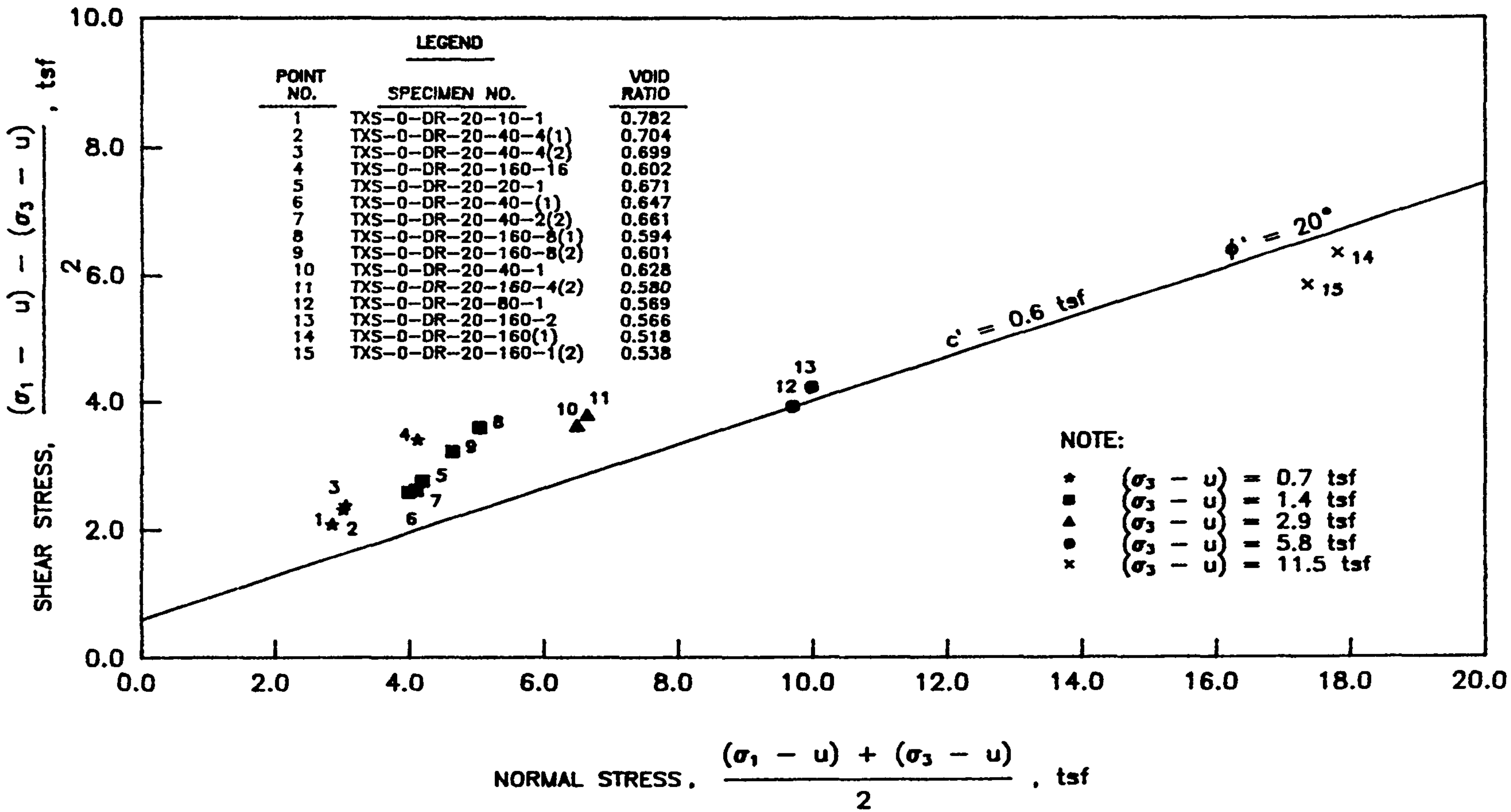

FIG. 58. Strengths of compacted specimens of buckshot clay sheared at a nominal water content of 20 percent.

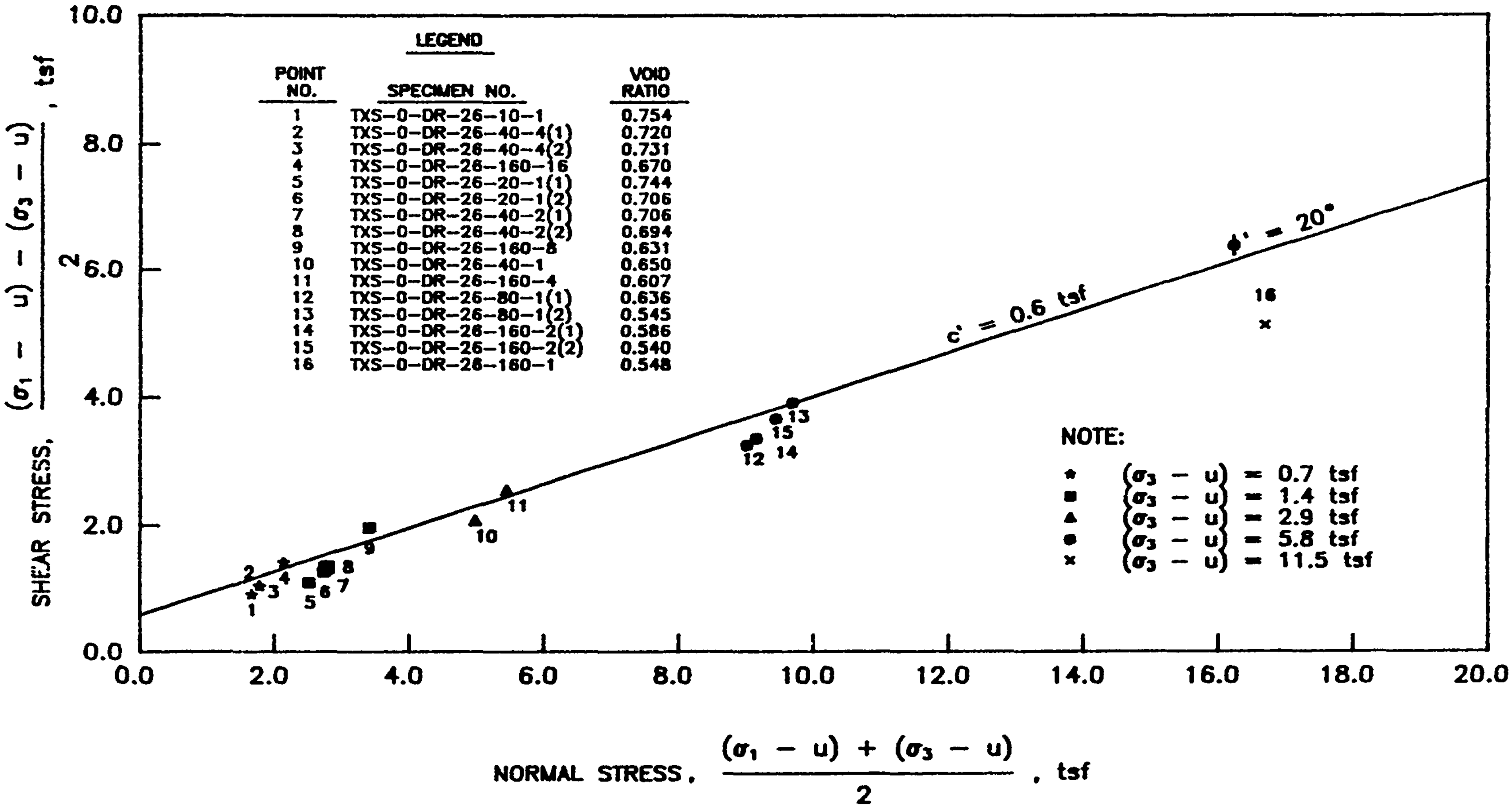

FIG. 59. Strengths of compacted specimens of buckshot clay sheared at a nominal water content of 26 percent.

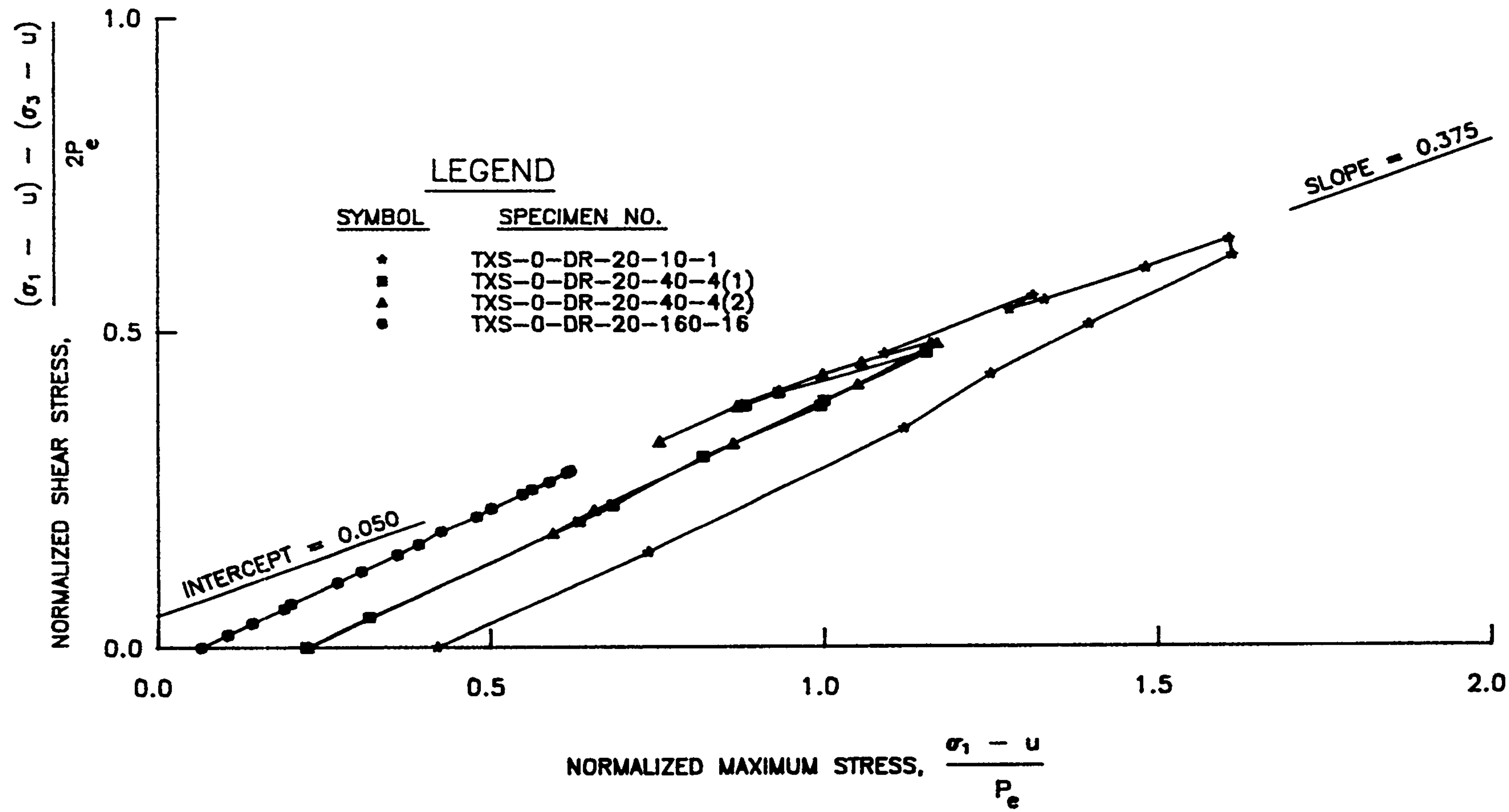

FIG. 60. Normalized stress path relationships for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 0.7 tsf (70 kPa).

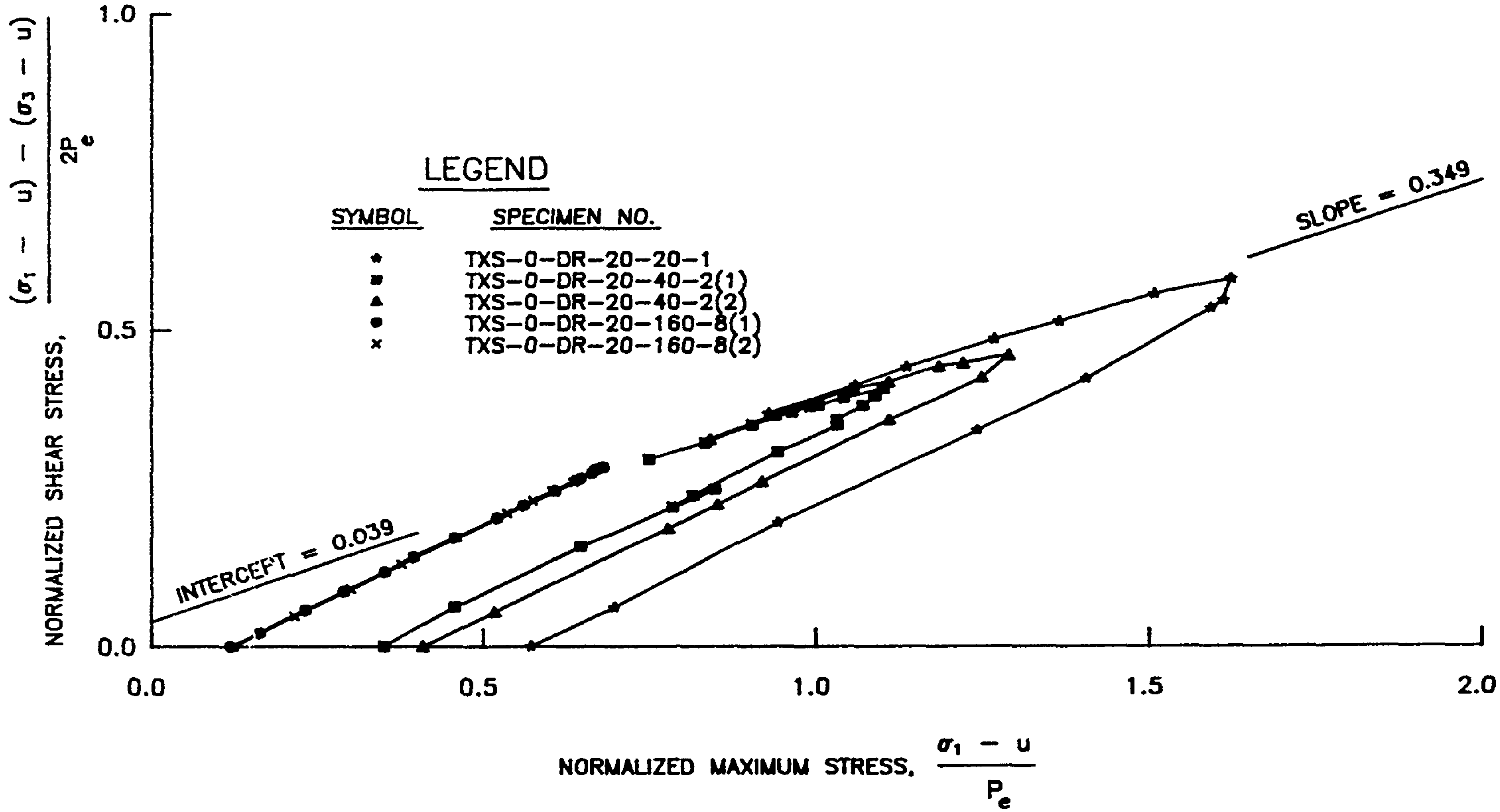

FIG. 61. Normalized stress path relationships for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 1.4 tsf (140 kPa).

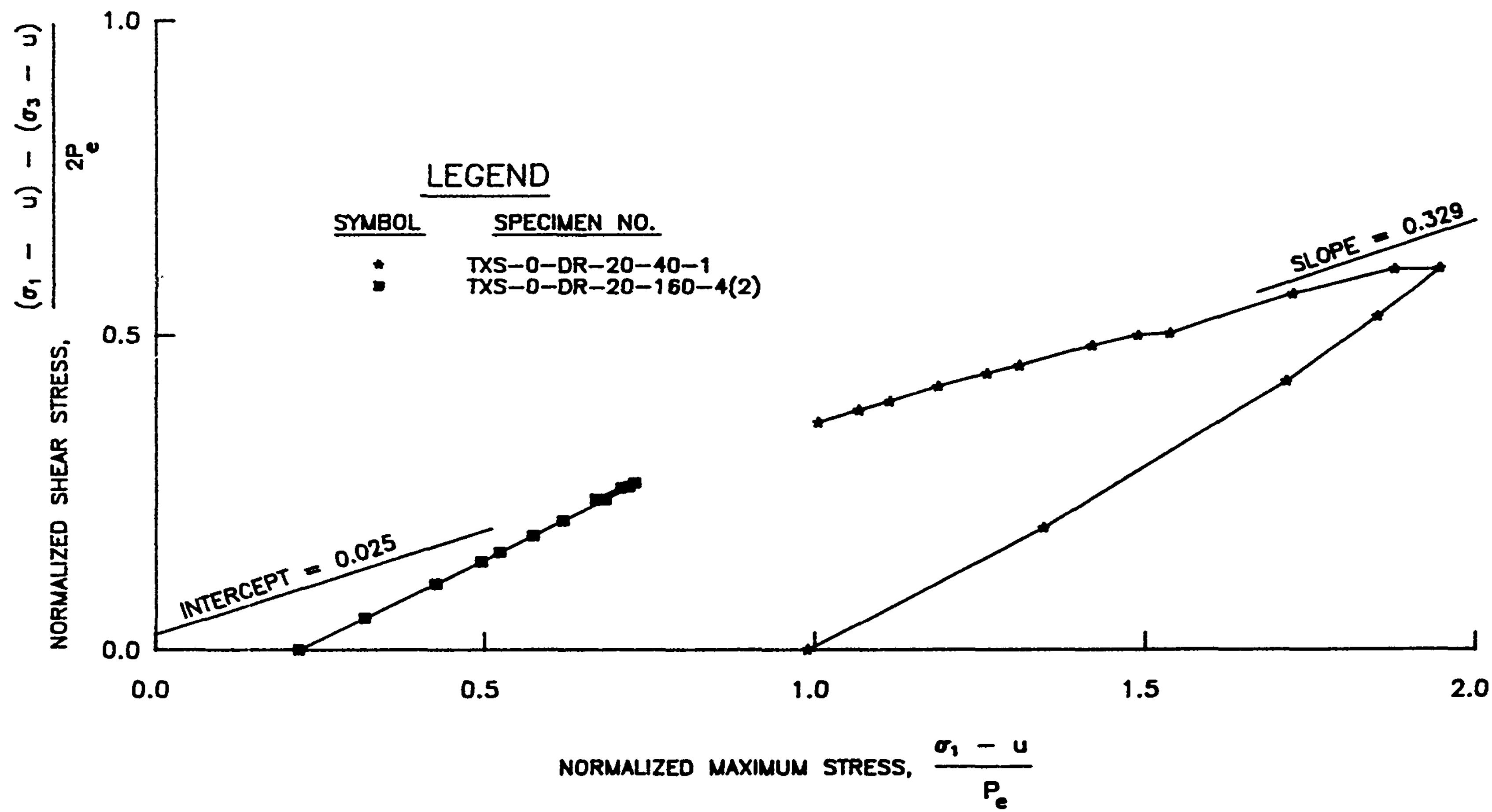

FIG. 62. Normalized stress path relationships for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 2.9 tsf (280 kPa).

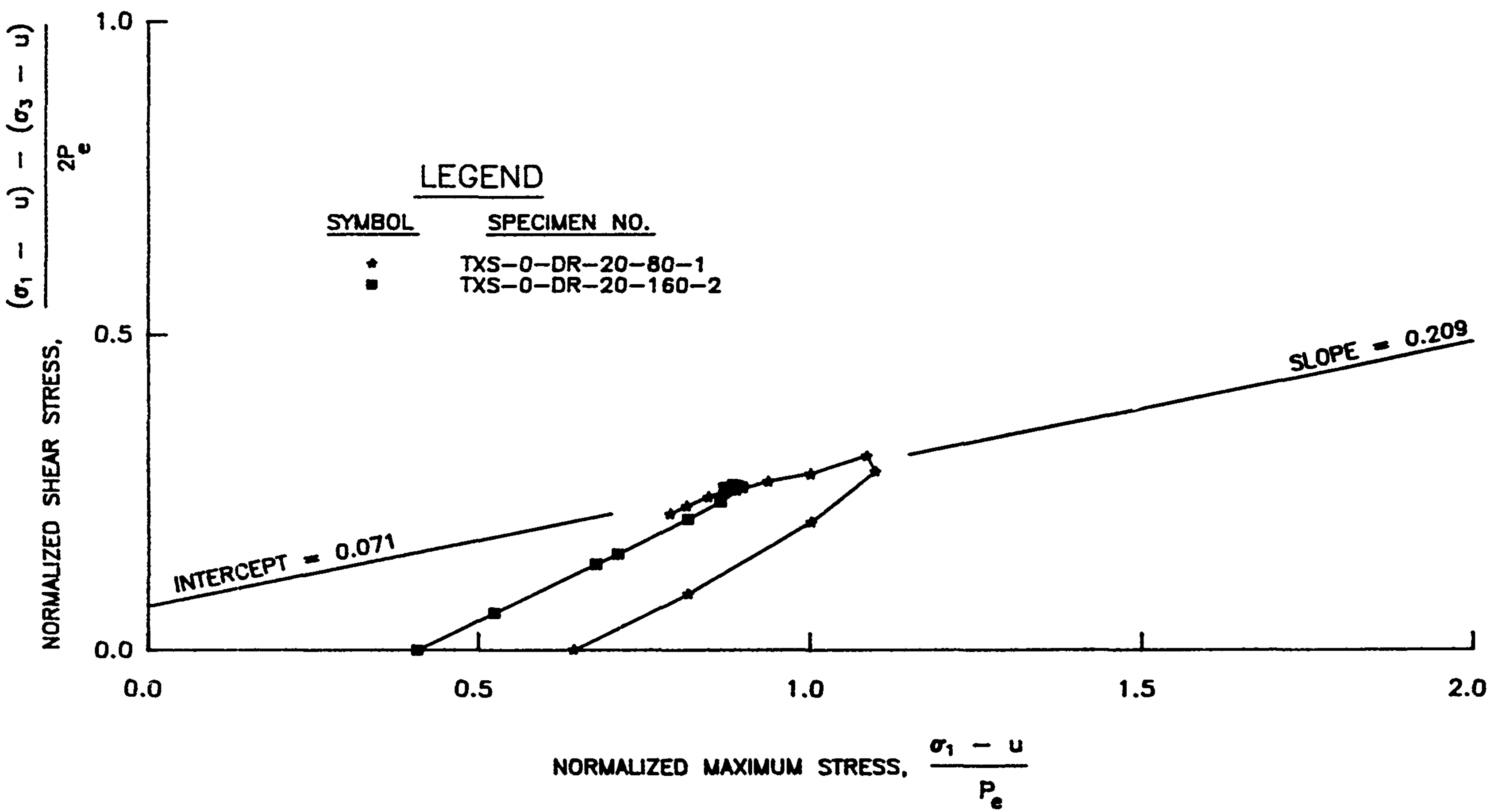

FIG. 63. Normalized stress path relationships for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 5.8 tsf (550 kPa).

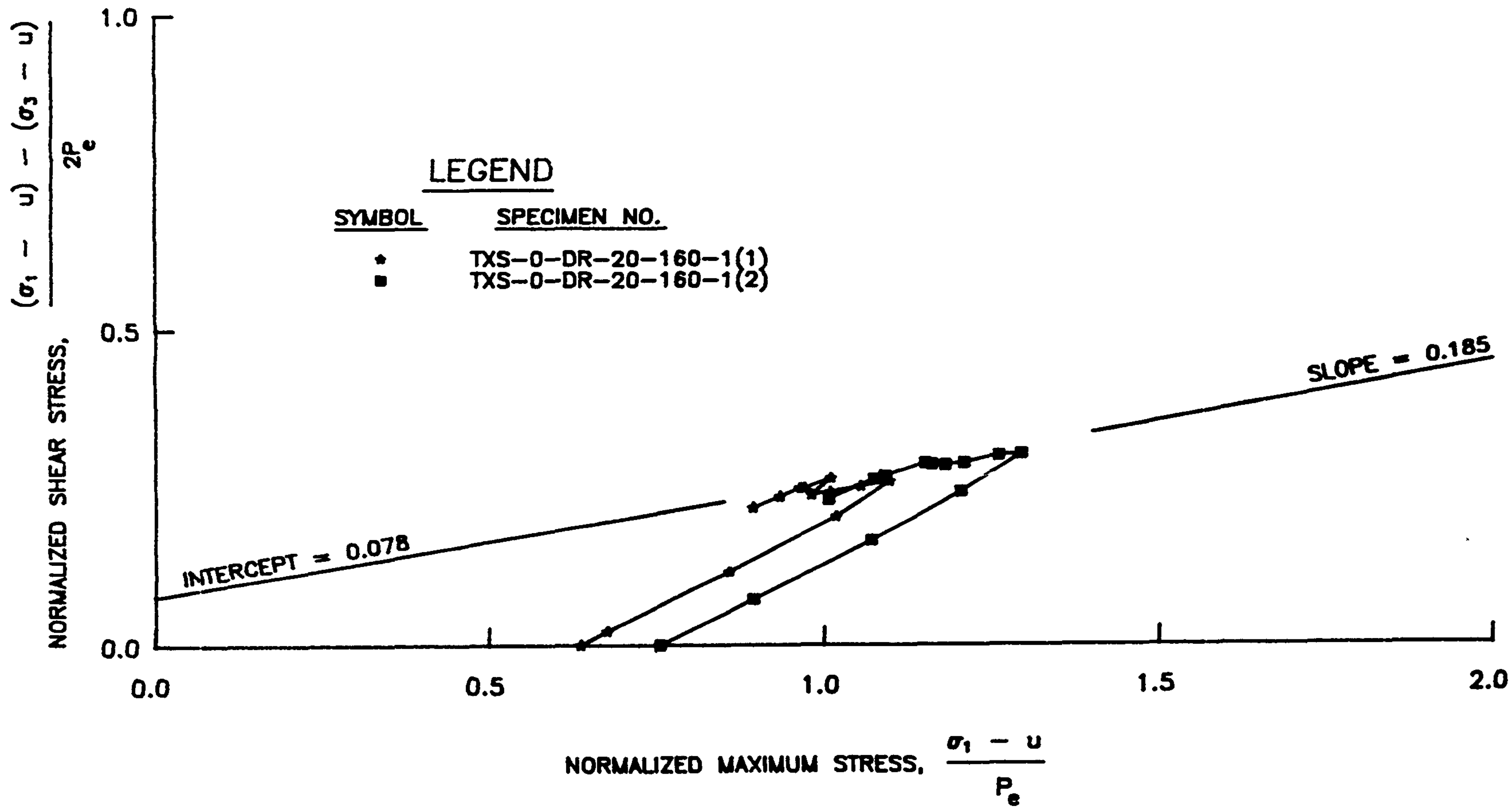

FIG. 64. Normalized stress path relationships for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 11.5 tsf (1.1 MPa).

normalized strength data for axial strains ranging from 7 to 17 percent for each specimen and are summarized in Table 4. These values of axial strain are comparable to the range of axial strains used to determine the Hvorslev strength parameters for saturated specimens. Correlation coefficients were typically 0.95 or greater. Although much confidence was gained from the excellent values for the coefficients of correlation, a fan of failure surfaces which appeared to be dependent upon confining pressures was formed. The slopes of the failure surfaces decreased from 0.37 to 0.21 as the confining pressures increased from 0.7 to 5.8 tsf (70 to 560 kPa). The meaning of various failure envelopes was not immediately clear.

Test results for unsaturated specimens compacted at a water content of 26 percent were also normalized for density variations using Equation 27. The normalized strengths of specimens sheared at stress states of 0.7, 1.4, 2.9, 5.8 or 11.5 tsf (70, 140, 280, 550 or 1100 kPa) are presented in Figures 65 through 69, respectively, and are also summarized in Table 4.

Because of the uncertainty regarding the interpretation of the strength parameters which are summarized in Table 4, the apparent shear strengths due to suction for unsaturated specimens were expressed in a form amenable to Mohr-Coulomb failure criteria using a form of Equation 33. To accomplish this, the normalized shear strength of a hypothetical saturated specimen, calculated from data given as Equations 28 and 29, was subtracted from the normalized strength of an unsaturated specimen. The differences were converted to an apparent shear strength due to suction, q_ψ, by multiplying by P_e, as shown in Equation 34:

$$q_\psi = P_e \left[\left[\frac{(\sigma_1 - u) - (\sigma_3 - u)}{2\ P_e} \right]_{\text{unsaturated}} - \left[\frac{C_e}{P_e} \frac{\cos \phi_e}{1 + \sin \phi_e} + \frac{(\sigma_1 - u)}{P_e} \frac{\sin \phi_e}{1 + \sin \phi_e} \right]_{\text{calculated}} \right] \tag{34}$$

Table 4. Normalized Strength Parameters for Compacted Specimens of Buckshot Clay

Confining Stress (σ_3 - u) tsf	kPa	Correlation Coefficient r	Intercept	Slope
Saturated specimens compacted at w = 20 and 26 percent				
---	---	0.948*	0.078*	0.185*
Unsaturated specimens compacted at w = 20 percent				
0.7	70	0.999	0.050	0.375
1.4	130	0.998	0.039	0.349
2.9	280	0.999	0.025	0.329
5.8	560	0.928	0.071	0.209
Unsaturated specimens compacted at w = 26 percent				
0.7	70	0.958	0.110	0.165
1.4	130	0.910	0.117	0.144
2.9	280	0.953	0.117	0.143
5.8	560	0.994	0.059	0.187
Treated clay specimens compacted at w = 20 percent				
0.7	70	0.999	0.069	0.344
1.4	130	0.998	0.060	0.298
2.9	280	0.999	0.065	0.251
5.8	560	0.990	0.087	0.210
11.5	1100	0.950	0.073	0.212
Treated clay specimens compacted at w = 26 percent				
0.7	70	0.988	-0.043	0.449
1.4	130	0.994	-0.104	0.490
2.9	280	0.976	0.004	0.302
5.8	560	0.955	-0.008	0.302
11.5	1100	0.996	-0.022	0.305

* Obtained from regression analysis of shear strengths of back pressure saturated specimens for this investigation.

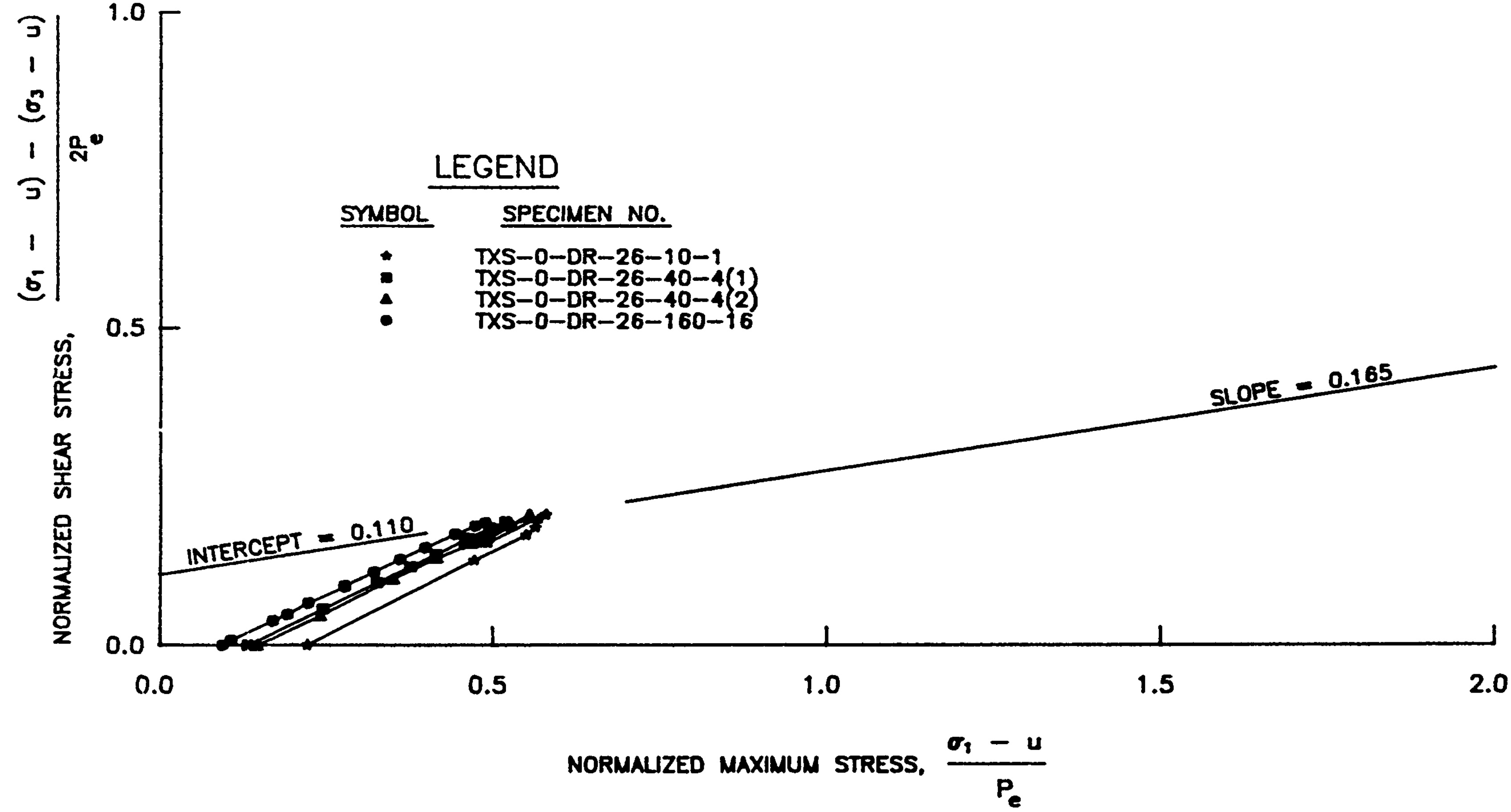

FIG. 65. Normalized stress path relationships for specimens of buckshot clay compacted at a nominal water content of 26 percent and sheared under a confining stress of 0.7 tsf (70 kPa).

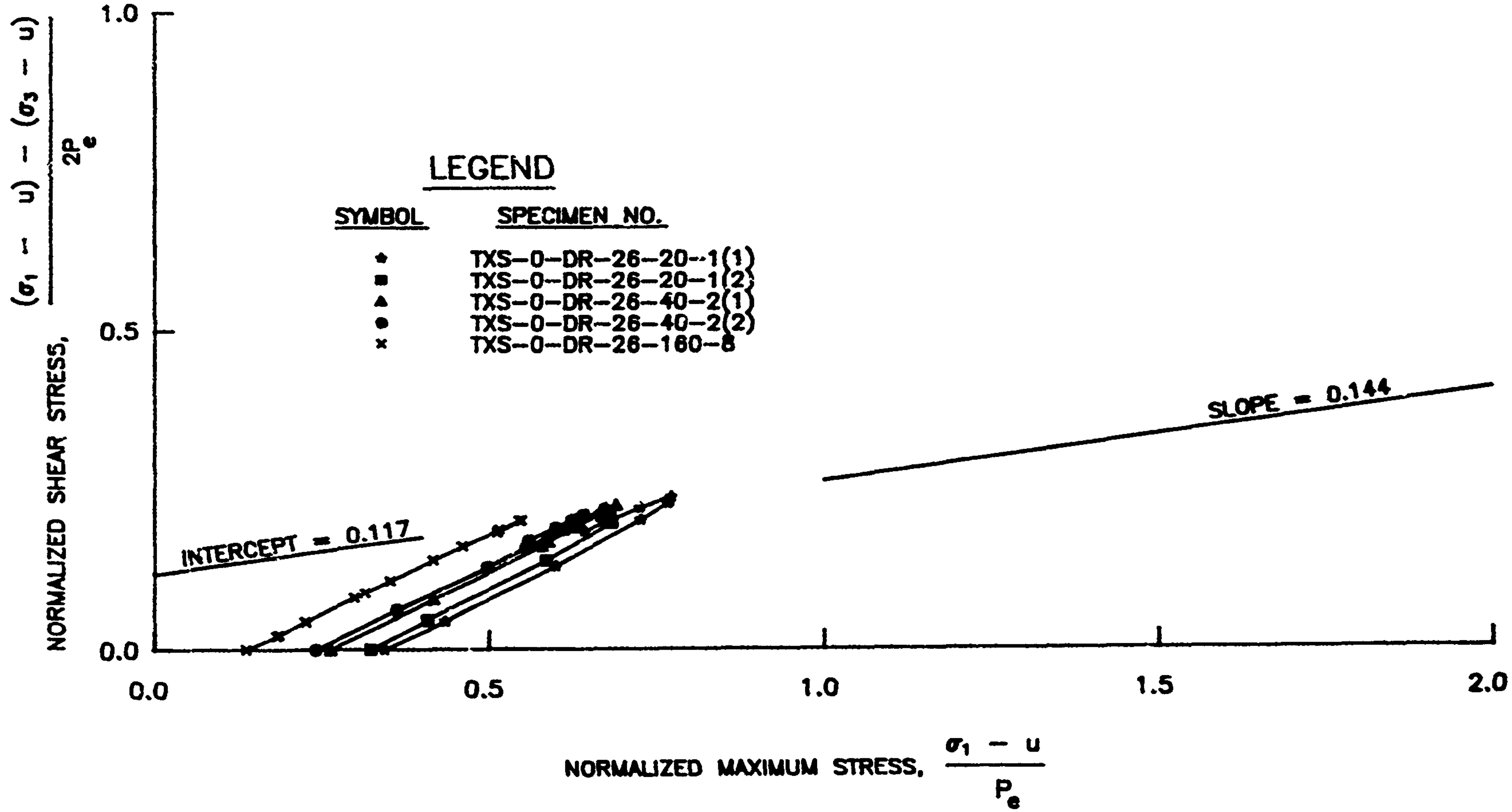

FIG. 66. Normalized stress path relationships for specimens of buckshot clay compacted at a nominal water content of 26 percent and sheared under a confining stress of 1.4 tsf (140 kPa).

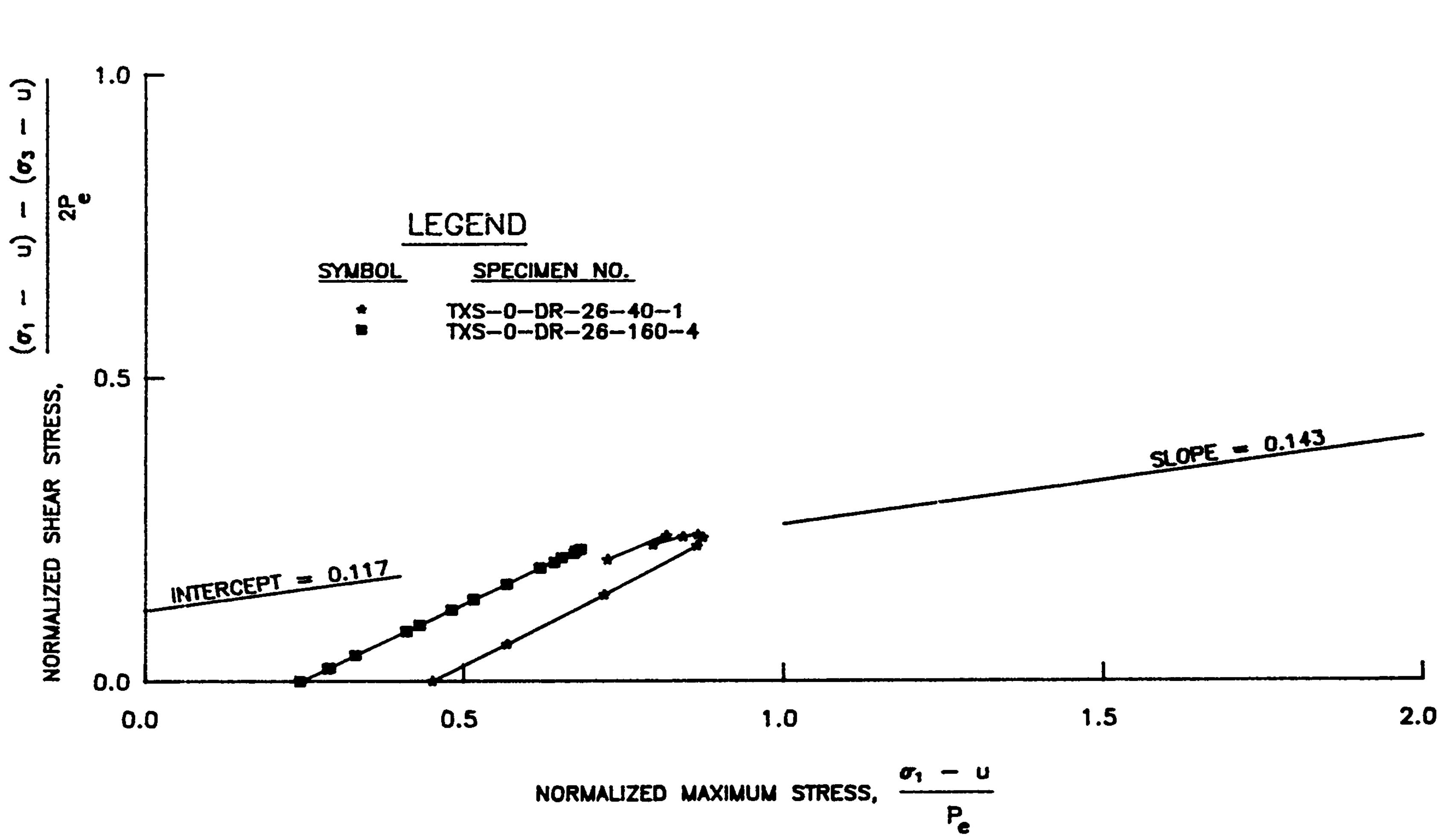

FIG. 67. Normalized stress path relationships for specimens of buckshot clay compacted at a nominal water content of 26 percent and sheared under a confining stress of 2.9 tsf (280 kPa).

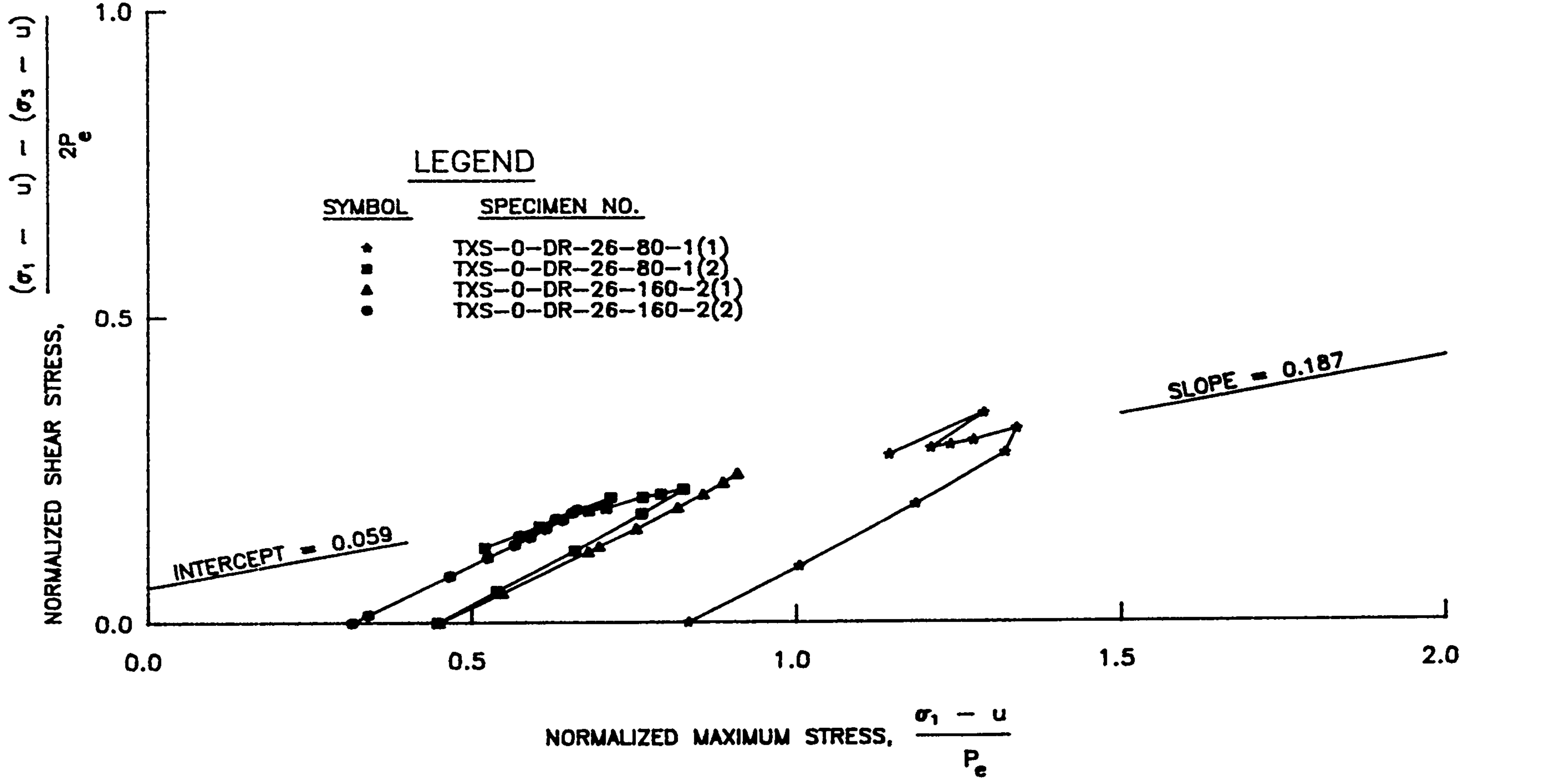

FIG. 68. Normalized stress path relationships for specimens of buckshot clay compacted at a nominal water content of 26 percent and sheared under a confining stress of 5.8 tsf (550 kPa).

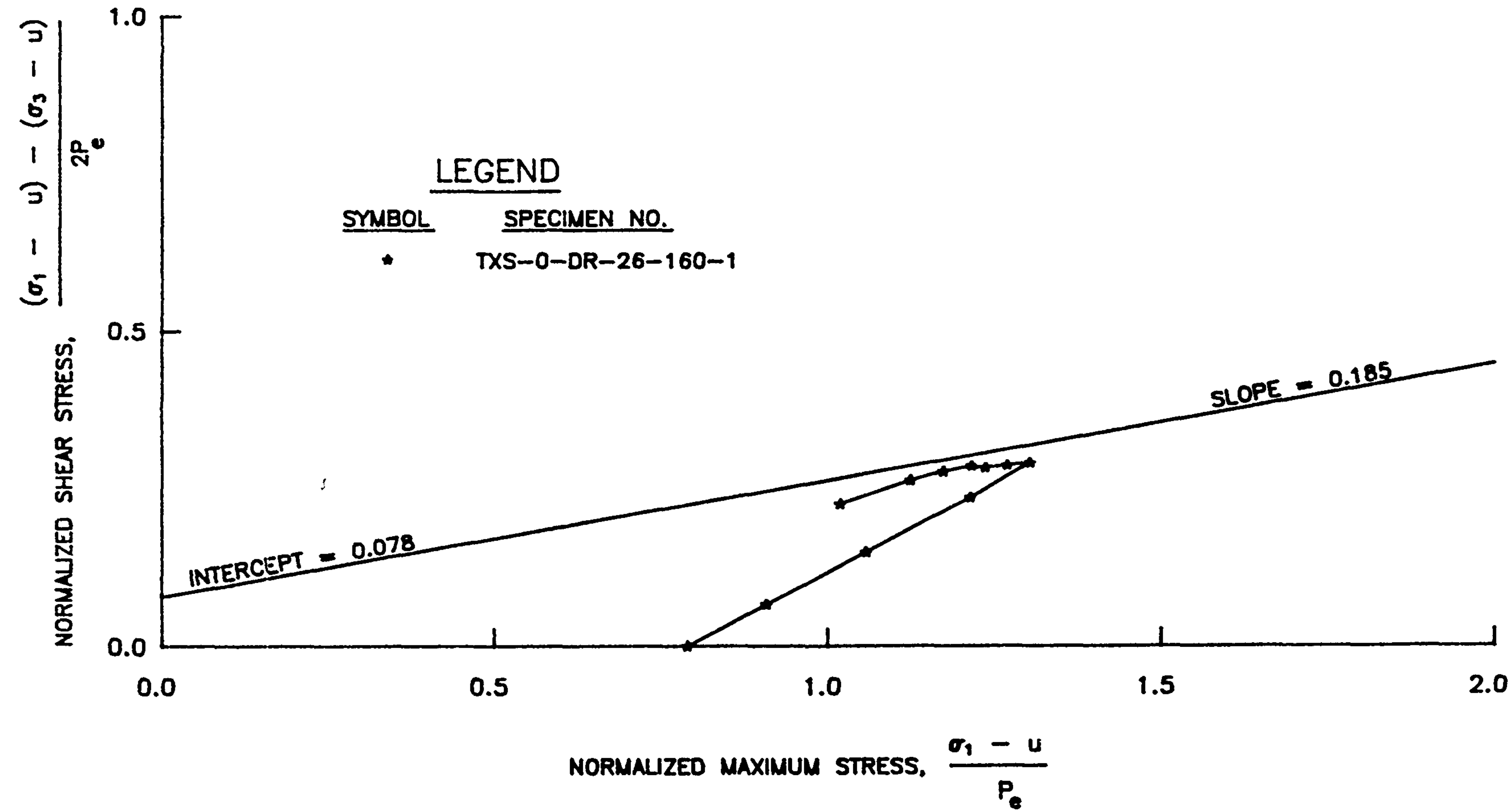

FIG. 69. Normalized stress path relationship for a specimen of buckshot clay compacted at a nominal water content of 26 percent and sheared under a confining stress of 11.5 tsf (1.1 MPa).

where

$(\sigma_1 - u)/P_e$ = normalized stress for an unsaturated specimen at any instant during the test

P_e = equivalent consolidation stress for an unsaturated specimen at any instant during the test

The strength of a saturated specimen was computed using the strength parameters given by Equations 28 and 29 and actual values of the normalized stress, $[(\sigma_1 - u)/P_e]$, for the unsaturated specimen. These data are summarized in Tables 5 and 6 for specimens compacted at water contents of 20 and 26 percent, respectively.

After differences of density for saturated and unsaturated specimens had been normalized, the calculated values of apparent shear strength due to suction for specimens compacted at a water content of 20 percent and tested at confining pressures of 0.7, 1.4 and 2.9 tsf (70, 140 and 280 kPa) were nearly constant; values ranged from 0.7 to 1.0 tsf (70 to 95 kPa). For specimens tested at an applied stress of 5.8 and 11.5 tsf (550 and 1100 kPa), the apparent shear strengths due to suction decreased to 0.3 tsf (30 kPa) and to zero, respectively. It is probable that the decrease of the apparent shear strength due to suction resulted as pore air became occluded and pore water tended to drain from the specimens, which is indicative of the transition from unsaturated to saturated behavior.

Calculated values of apparent shear strength due to suction, expressed as a function of axial strain for specimens sheared at confining pressures of 0.7, 1.4, 2.9, 5.8 or 11.5 tsf (70, 140, 280, 550 or 1100 kPa), are presented in Figures 70 through 74, respectively. As can be seen from these data, the maximum strength due to suction occurred for axial strains ranging from 7 to 17 percent, which is consistent with the data used for the regression analyses that are summarized in Table 4.

The data presented in Figures 75 through 77 are calculated values of apparent shear strength due to suction expressed as a function of axial strain for unsaturated specimens compacted at a nominal water content of 26 percent. The apparent shear strengths due to suction for specimens consolidated by 0.7, 1.4 or 2.9 tsf (70, 140 or 280 kPa),

Table 5. Influence of Suction on the Shear Strength of Specimens of Buckshot Clay Tested at a Water Content of 20 Percent

Test Number	Saturation at Failure S %	Apparent Shear Strength Due to Suction q_ψ tsf	Apparent Shear Strength Due to Suction q_ψ kPa	Suction at Failure h_t* tsf	Suction at Failure h_t* kPa	Arctan q_ψ/h_t deg
TXS-0-DR-20-10-1	67	0.78	75	9.8	940	4.6
TXS-0-DR-20-40-4(1)	74	0.85	81	4.0	380	12.0
TXS-0-DR-20-40-4(2)	73	0.86	82	3.8	360	12.8
TXS-0-DR-20-160-16	86	1.05	101	3.8	360	15.4
TXS-0-DR-20-20-1	74	0.88	84	9.0	850	5.6
TXS-0-DR-20-40-2(1)	78	0.73	70	---	---	----
TXS-0-DR-20-40-2(2)	74	0.82	79	3.1	300	14.8
TXS-0-DR-20-160-8(1)	88	0.98	94	3.7	350	14.8
TXS-0-DR-20-160-8(2)	89	0.80	77	---	---	----
TXS-0-DR-20-40-1	77	0.98	94	4.7	450	11.8
TXS-0-DR-20-160-4(2)	91	0.74	71	3.2	310	13.0
TXS-0-DR-20-80-1	90	0.22	21	3.2	310	3.9
TXS-0-DR-20-160-2	91	0.34	33	0.8	80	23.0
TXS-0-DR-20-160-1(1)	100	-0.01	-1	0.2	20	----
TXS-0-DR-20-160-1(2)	97	-0.04	-4	0.1	10	----

* Note: h_m is approximately equal to h_t.

Table 6. Influence of Suction on the Shear Strength of Specimens of Buckshot Clay Tested at a Water Content of 26 Percent

Test Number	Saturation at Failure S %	Apparent Shear Strength Due to Suction q_ψ tsf	kPa	Suction at Failure h_t* tsf	kPa	Arctan q_ψ/h_t deg
TXS-0-DR-26-10-1	98	0.08	8	1.0	100	4.6
TXS-0-DR-26-40-4(1)	97	0.10	10	---	---	----
TXS-0-DR-26-40-4(2)	98	0.12	12	0.6	60	11.3
TXS-0-DR-26-160-16	100	0.17	16	---	---	----
TXS-0-DR-26-20-1(1)	98	0.06	6	0.9	90	3.8
TXS-0-DR-26-20-1(2)	100	0.07	7	1.0	100	4.0
TXS-0-DR-26-40-2(1)	100	0.09	9	---	---	----
TXS-0-DR-26-40-2(2)	100	0.05	5	0.4	40	0.7
TXS-0-DR-26-160-8	100	0.20	2	---	---	----
TXS-0-DR-26-40-1	100	0.03	3	1.1	110	----
TXS-0-DR-26-160-4	100	0.16	15	---	---	----
TXS-0-DR-26-80-1(1)	100	-0.15	-14	---	---	----
TXS-0-DR-26-80-1(2)	100	-0.10	-10	---	---	----
TXS-0-DR-26-160-2(1)	100	0.04	4	---	---	----
TXS-0-DR-26-160-2(2)	100	-0.31	-30	---	---	----
TXS-0-DR-26-160-1	100	-0.43	-41	---	---	----

* Note: h_m is approximately equal to h_t.

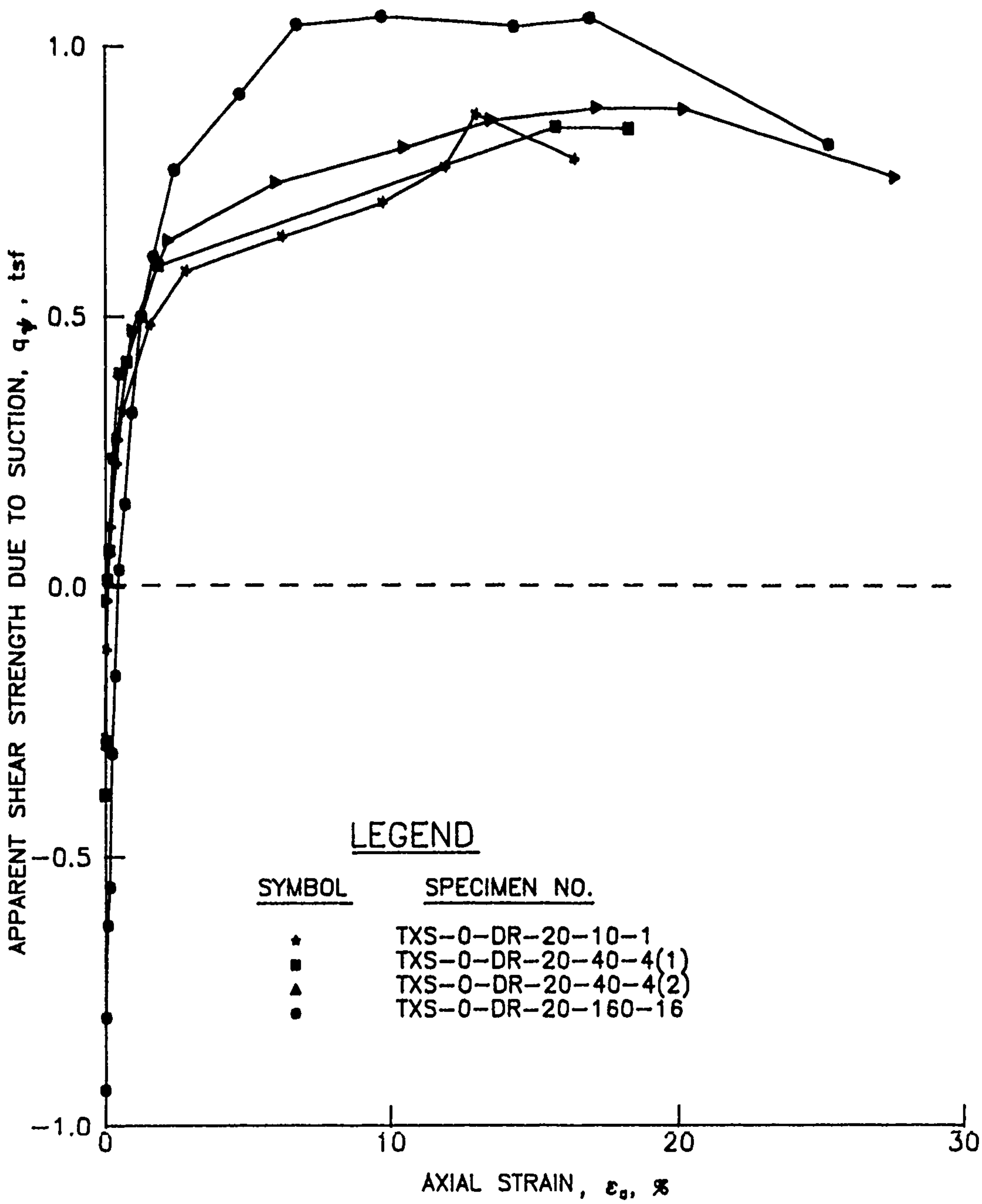

FIG. 70. Apparent shear strength due to suction for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 0.7 tsf (70 kPa).

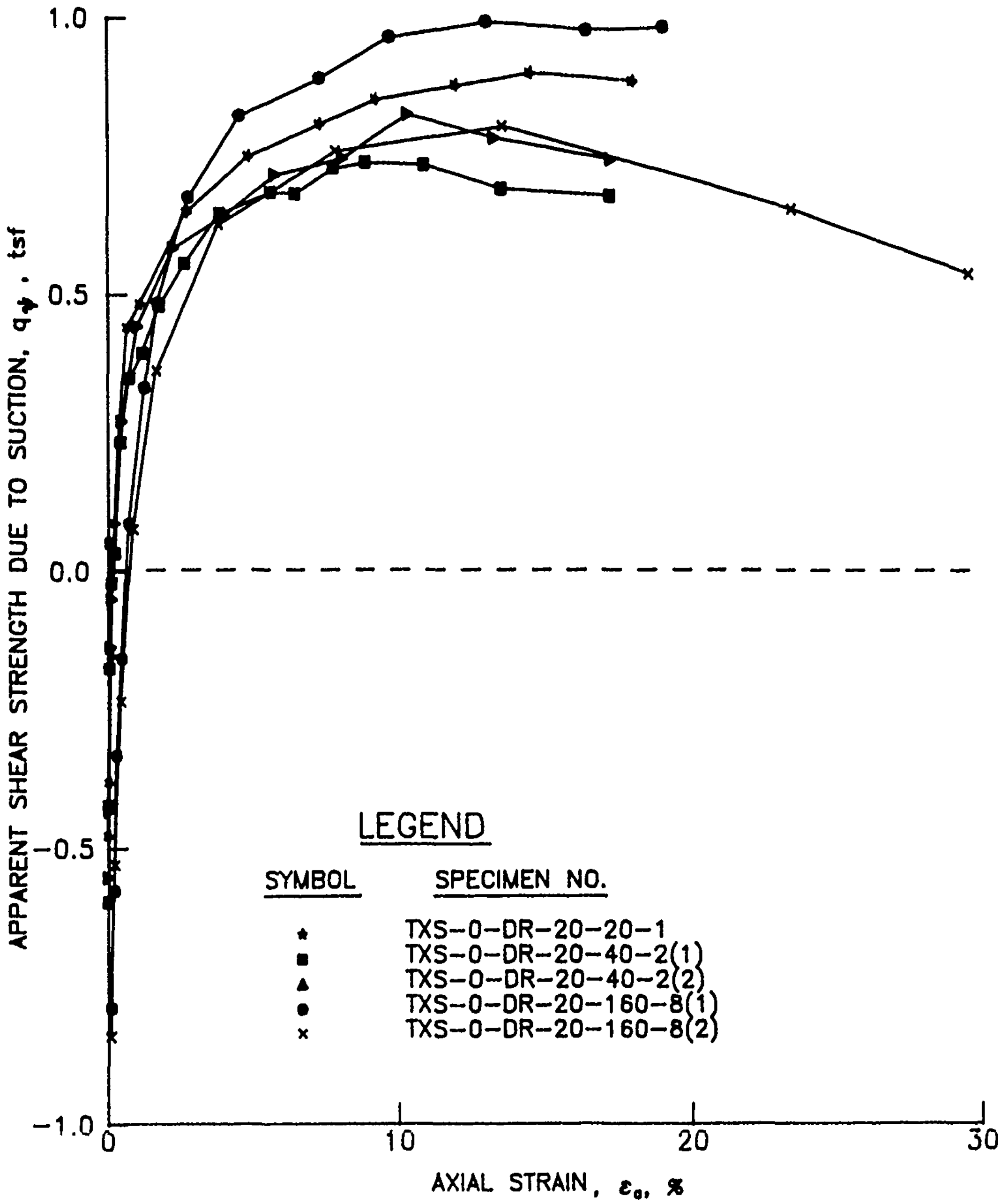

FIG. 71. Apparent shear strength due to suction for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 1.4 tsf (140 kPa).

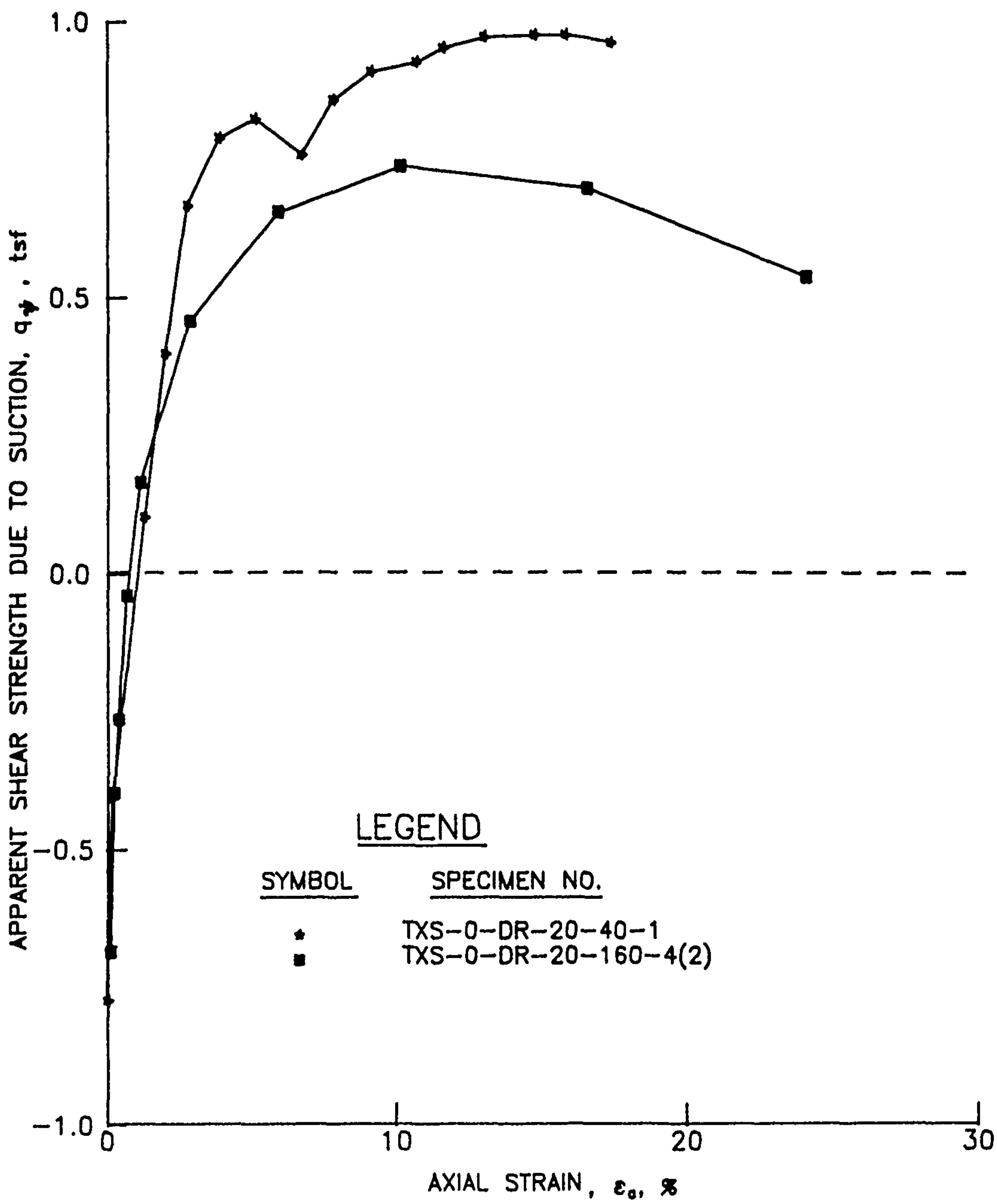

FIG. 72. Apparent shear strength due to suction for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 2.9 tsf (280 kPa).

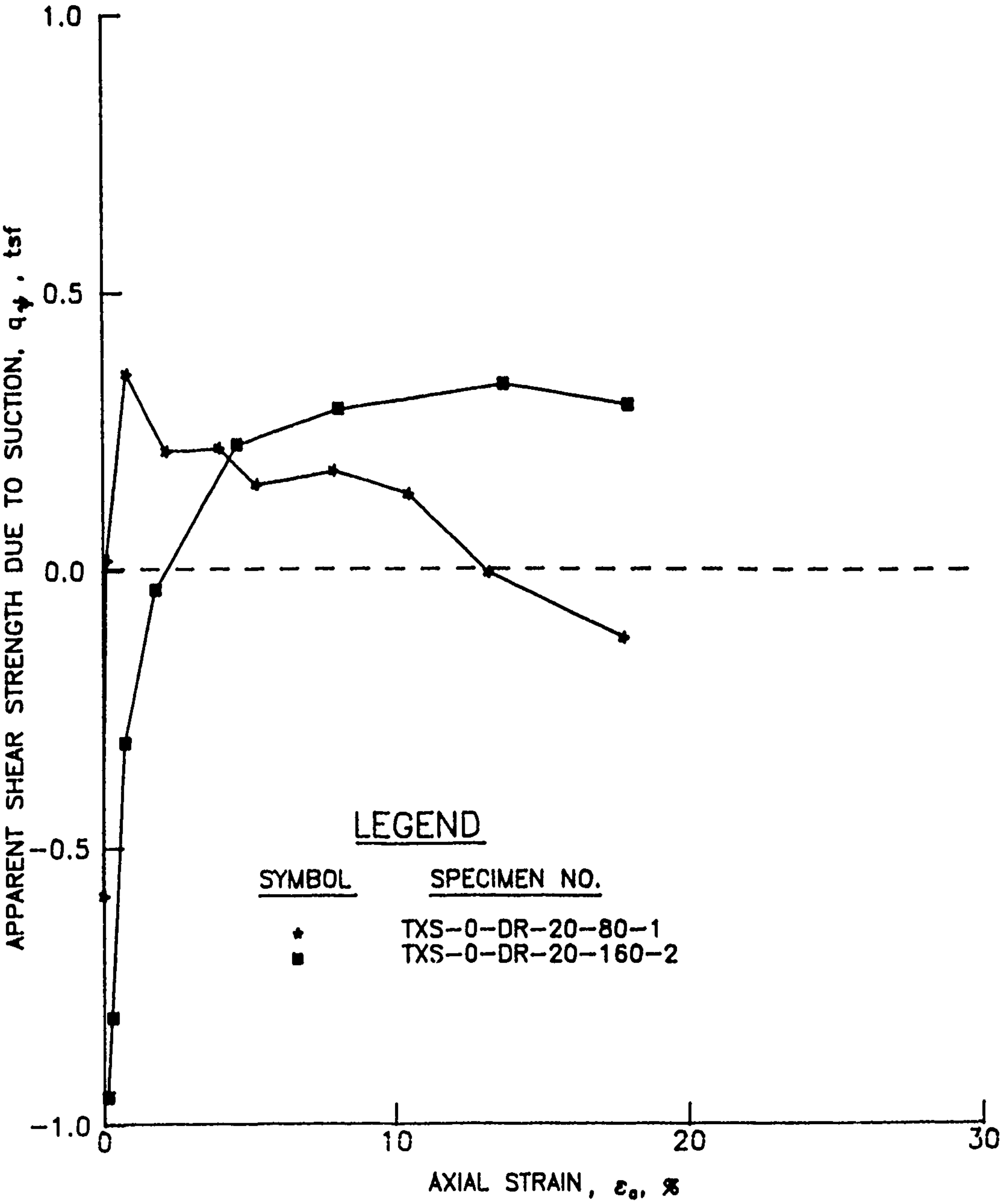

FIG. 73. Apparent shear strength due to suction for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 5.8 tsf (550 kPa).

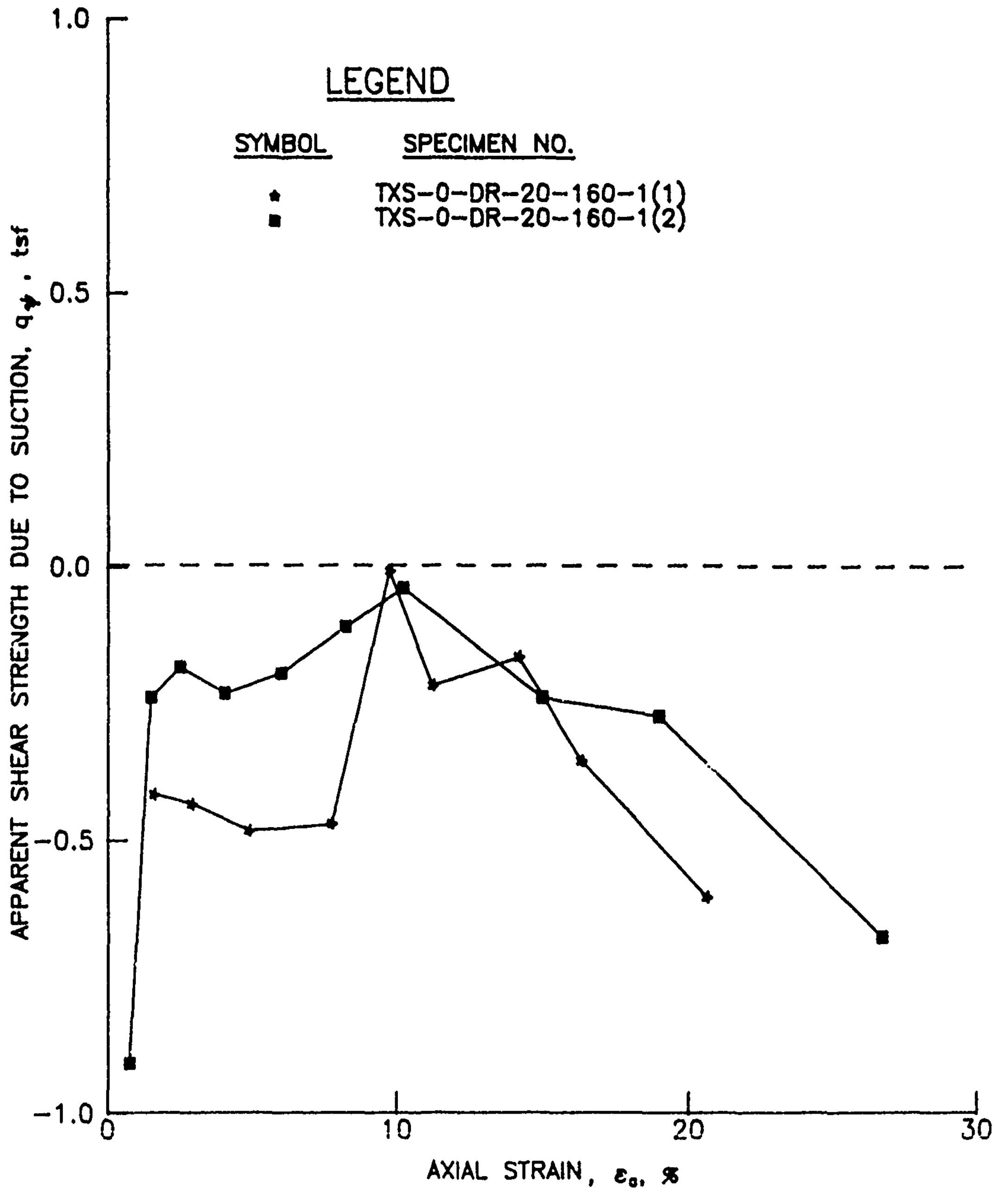

FIG. 74. Apparent shear strength due to suction for specimens of buckshot clay compacted at a nominal water content of 20 percent and sheared under a confining stress of 11.5 tsf (1.1 MPa).

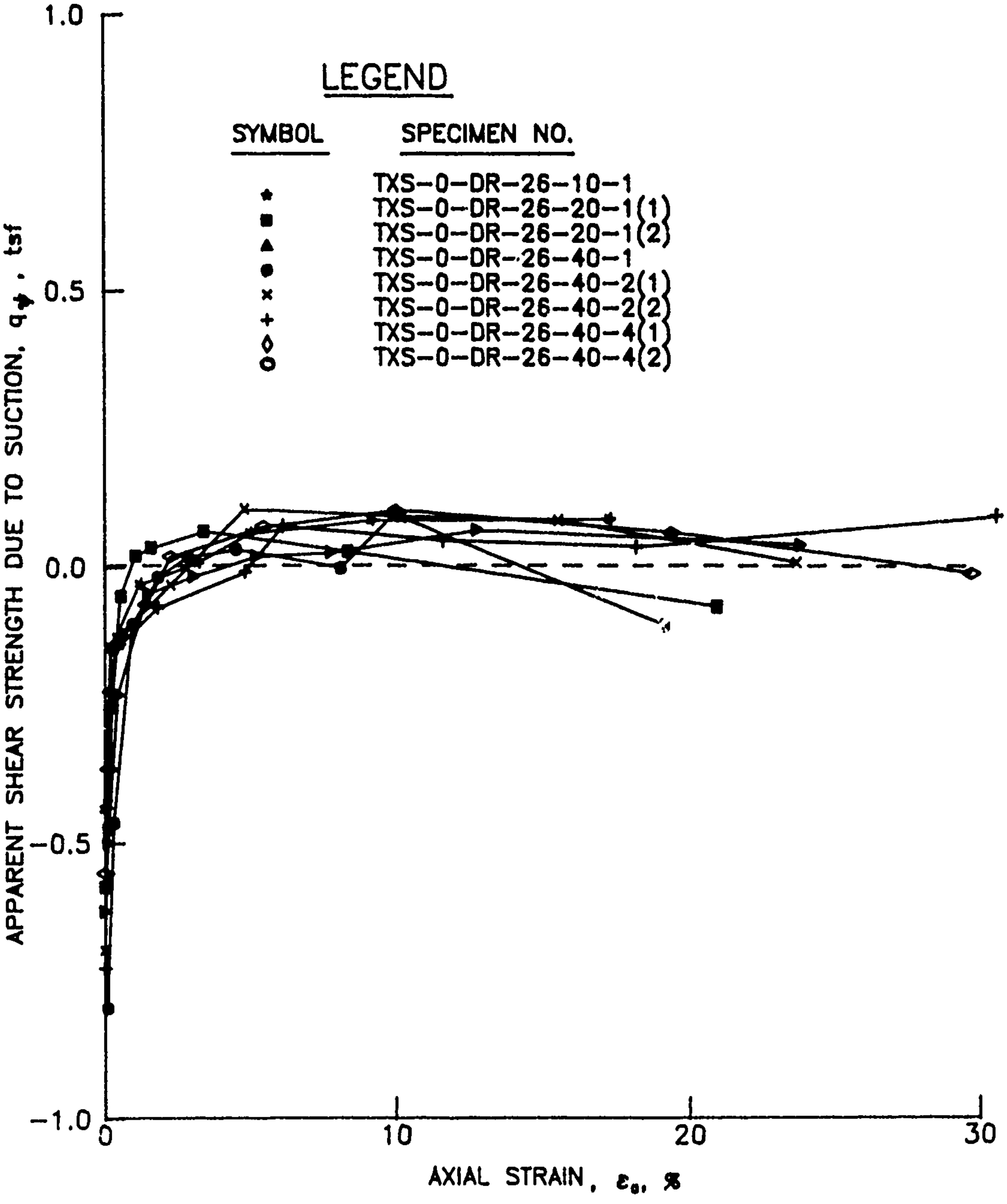

FIG. 75. Apparent shear strength due to suction for specimens of buckshot clay compacted at a nominal water content of 26 percent and sheared under confining stresses of 0.7, 1.4 or 2.9 tsf (0.7, 1.4 or 2.9 kPa).

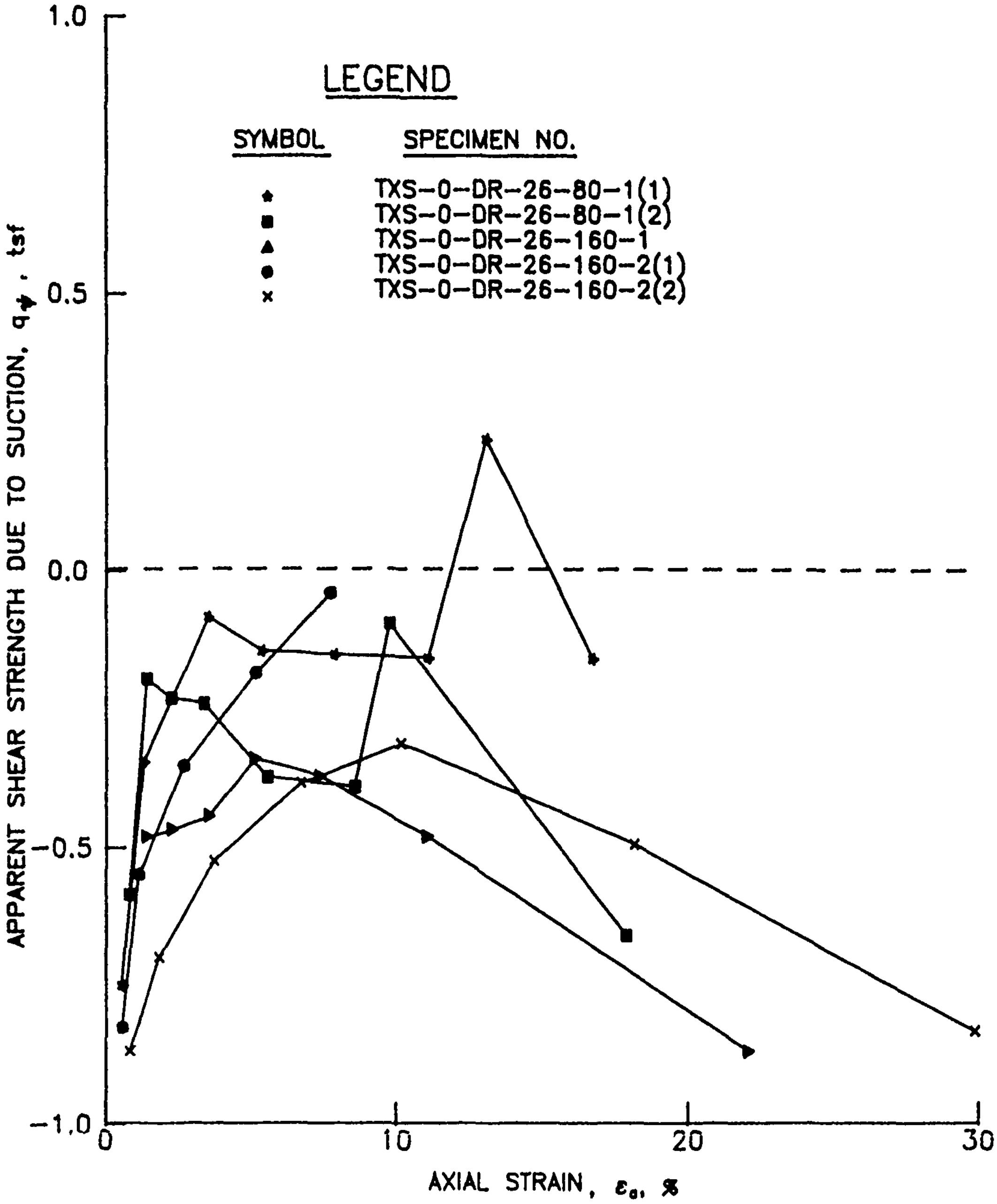

FIG. 76. Apparent shear strength due to suction for specimens of buckshot clay compacted at a nominal water content of 26 percent and sheared under confining stresses of 5.8 or 11.5 tsf (550 or 1100 kPa).

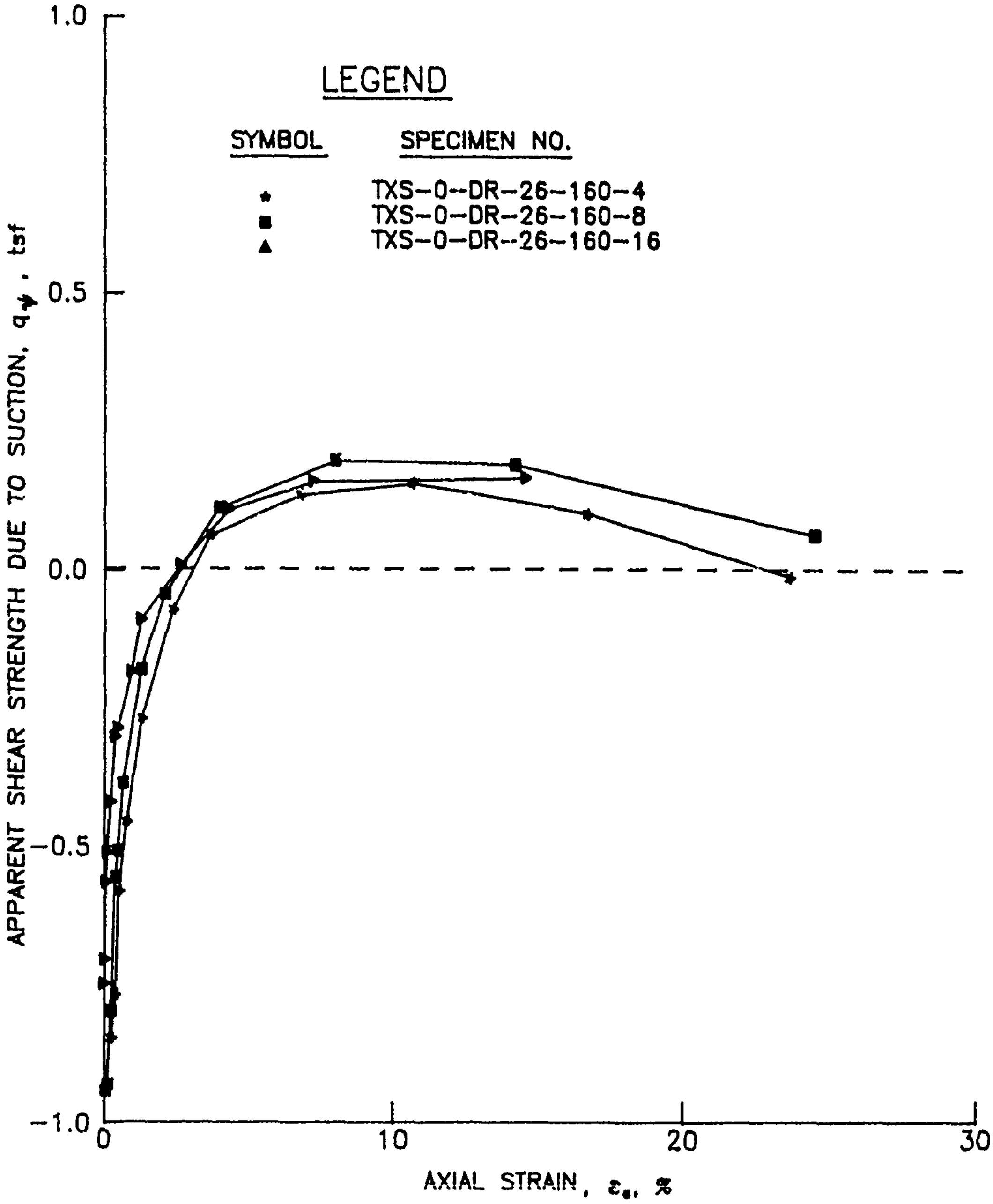

FIG. 77. Apparent shear strength due to suction for specimens of buckshot clay compacted at a nominal water content of 26 percent, consolidated by 11.5 tsf (1.1 MPa), and sheared under confining stresses of 0.7, 1.4 or 2.9 tsf (0.7, 1.4 or 2.9 kPa).

which are presented in Figure 75, were similar to the strengths of saturated specimens; values were generally less than 0.1 tsf (10 kPa). A second group of test results, which are presented in Figure 76, was obtained from specimens tested at confining pressures of 5.8 or 11.5 tsf (550 or 1100 kPa). Calculated values of the apparent shear strength due to suction were slightly less than the shear strengths of saturated specimens. Data presented in Figure 77 were obtained from specimens consolidated to 11.5 tsf (1.1 MPa) and rebounded to 0.7, 1.4 or 2.9 tsf (70, 140 or 280 kPa) prior to shear. Apparent shear strengths due to suction were approximately 0.2 tsf (20 kPa).

Although the values of apparent shear strength due to suction for specimens compacted at a nominal water content of 26 percent did not appear to be blatantly erroneous, the data presented in Figures 76 and 77 were suspect; presumably the strengths of these specimens should have been comparable to the strengths of saturated specimens because the calculated degrees of saturation at failure were greater than 100 percent. Two explanations were considered: (a) the volume change measurements were incorrect because dissolved air in the chamber fluid came out of solution as the specimen was rebounded and (b) the tests were conducted too rapidly to allow equalization of pore pressures.

Although care was taken to ensure that the inner chamber was saturated before tests were initiated, dissolved air in the water which filled the inner chamber could come out of solution as the specimen was rebounded. If this condition occurred, free air in the inner chamber would result in volume change measurements which were too large and equivalent consolidation stresses which were too small. Consequently, calculated values of the apparent shear strength due to suction would be erroneous, although the values could be either too large or too small. Calibration tests were conducted to obtain a correction factor for the error caused by air in the chamber fluid. Unfortunately, a correction factor could not be determined because the magnitude of the error was fairly small and the calibrations were not very repeatable.

As indicated in the section entitled "Triaxial Tests on Unsaturated Specimens", the length of time for testing unsaturated specimens should have been increased to ensure that pore pressures had equalized.

If tests were conducted too rapidly, the induced pore pressure would not have dissipated and the applied stresses, $[(\sigma_1 - u) + (\sigma_3 - u)]/2$, would be different than the assumed condition of $u = 0$. During the shear of more normally consolidated specimens, such as those presented in Figure 76, positive pore pressures would be induced. The strengths of these specimens would be slightly less than the shear strengths of fully drained specimens where $u = 0$ because the applied stress conditions would be slightly less than the assumed conditions. For more overconsolidated specimens, such as those presented in Figure 77, negative pore water pressures would be induced. These specimens would be slightly stronger than fully drained specimens because the applied stress conditions would be slightly greater than the assumed conditions.

From the data presented in Figure 77, it was noted that the apparent shear strengths due to suction for specimens compacted at a water content of 26 percent, consolidated by 11.5 tsf (1.1 MPa) and rebounded prior to shear were approximately 0.1 to 0.2 tsf (10 to 20 kPa) larger than the shear strengths of saturated specimens. Similarly, the apparent shear strengths due to suction for specimens compacted at a water content of 20 percent, consolidated to 11.5 tsf (1.1 MPa) and rebounded to 0.7, 1.4 or 2.9 tsf (70, 140 or 280 kPa) prior to shear were also 0.1 to 0.2 tsf (10 to 20 kPa) larger than the apparent shear strengths due to suction for specimens which were consolidated by stresses of 0.7, 1.4 or 2.9 tsf (70, 140 or 280 kPa) prior to shear. After consideration of possible errors that were introduced by testing procedures, it was concluded that the strengths due to suction for the specimens identified above should be reduced 0.1 to 0.2 tsf (10 to 20 kPa). As a result of this decision, the apparent shear strengths due to suction for specimens compacted at a water content of 26 percent were approximately zero. Likewise, the apparent shear strengths due to suction for specimens compacted at a water content of 20 percent were about 0.85 tsf (80 kPa) provided the degree of saturation at failure was less than 85 to 90 percent.

Strength of Clay Treated with Potassium Chloride

The results of tests on specimens which had been treated with potassium chloride were analyzed using procedures similar to those procedures used for analyzing untreated specimens of buckshot clay. Stress path data did little to assist in the assessment of the influence of suction on shear strengths because the specimens were tested in a drained condition. Furthermore, the densities of the treated specimens were somewhat different than the densities of untreated specimens. Consequently, the data were normalized for density variations using Equation 27. Test results for specimens compacted at water contents of 20 and 26 percent are presented in Figures 78 and 79, respectively. Regression analyses were conducted on the normalized shear strength data recorded at axial strains ranging from 7 to 17 percent and are summarized in Table 4. As the consolidation stresses were increased from 0.7 to 11.5 tsf (70 to 1100 kPa), the slopes of the normalized strength envelopes for specimens compacted at a water content of 20 percent decreased from 0.34 to 0.21. Similarly, the slopes of the normalized strength envelopes for specimens compacted at a water content of 26 percent decreased from 0.49 to 0.30 as the consolidation stresses were increased.

The apparent shear strengths due to suction were calculated using Equation 34. These data, which are summarized in Table 7, are also presented in Figures 80 and 81 as apparent shear strength due to suction versus axial strain for treated specimens compacted at water contents of 20 and 26 percent, respectively. For specimens compacted at a water content of 20 percent, the apparent shear strengths due to suction decreased from approximately 0.7 to 0.5 tsf (70 to 50 kPa) as the degree of saturation at failure increased from 74 to 100 percent. Recall that the apparent shear strength due to suction for untreated specimens decreased from approximately 0.85 tsf (80 kPa) to zero as the degree of saturation at failure increased from 67 to 100 percent. Likewise, the apparent shear strengths due to suction for treated specimens compacted at a water content of 26 percent were approximately 0.3 tsf (30 kPa), as compared to approximately zero for untreated specimens. An explanation was not immediately available.

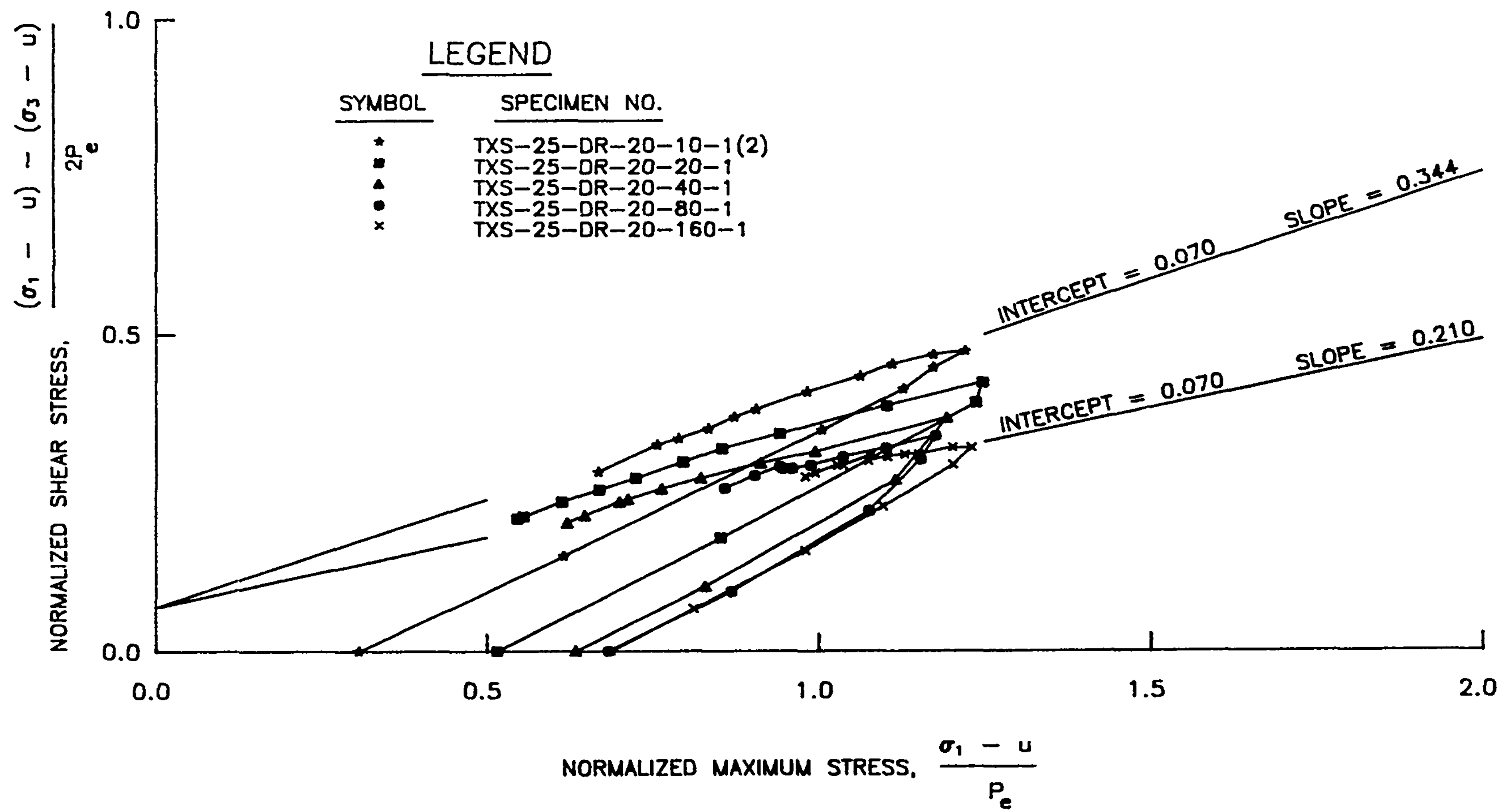

FIG. 78. Normalized stress path relationships for specimens of buckshot clay treated with potassium chloride prior to compaction at a nominal water content of 20 percent.

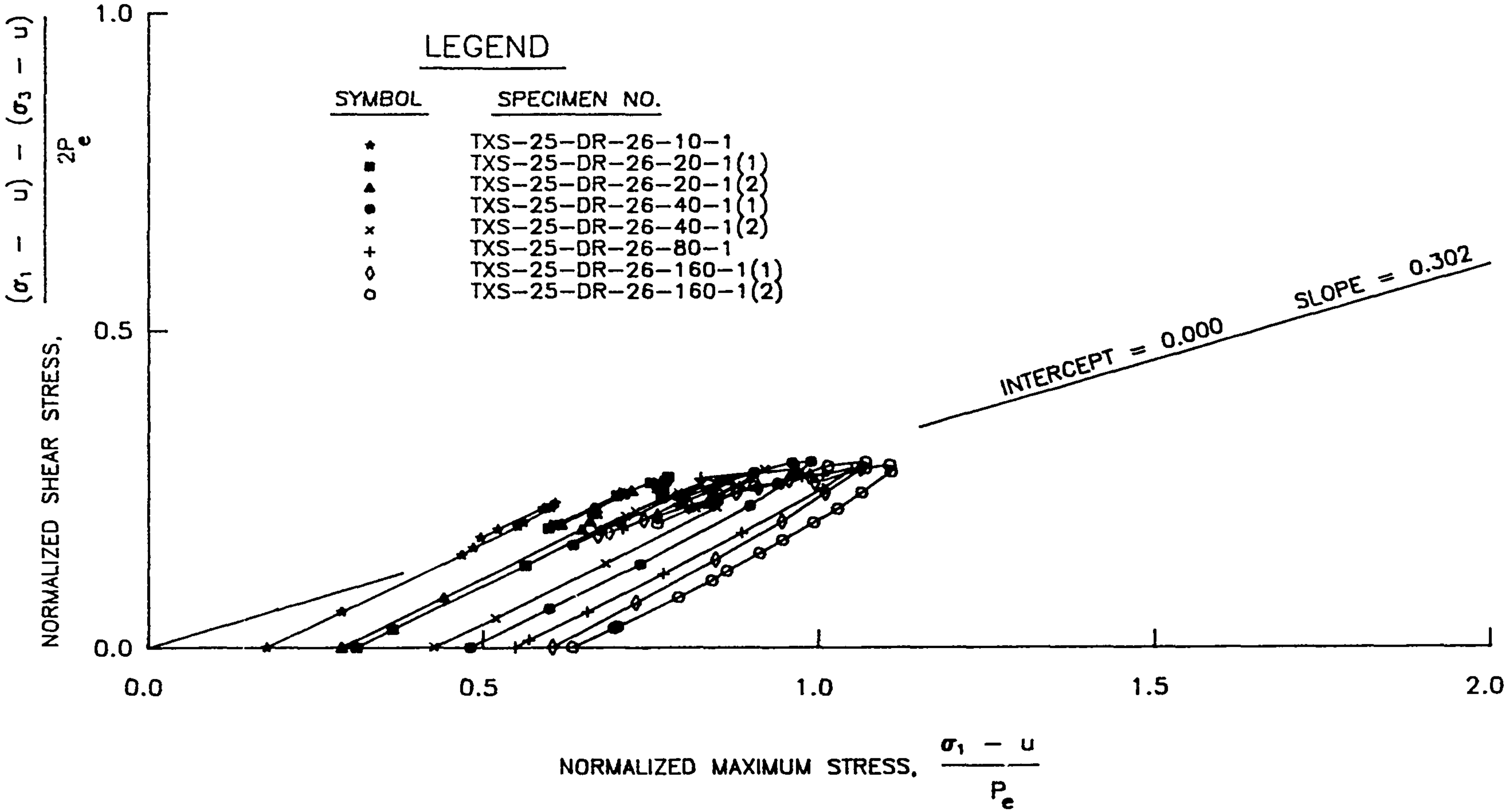

FIG. 79. Normalized stress path relationships for specimens of buckshot clay treated with potassium chloride prior to compaction at a nominal water content of 26 percent.

Table 7. Influence of Suction on the Shear Strength of Treated Specimens of Buckshot Clay

Test Number	Saturation at Failure S %	Apparent Shear Strength Due to Suction q_ϕ tsf	kPa	Suction at Failure h_t tsf	MPa
TXS-25-DR-20-10-1(2)	74	0.74	71	30.6	2.9
TXS-25-DR-20-20-1	80	0.57	55	30.8	3.0
TXS-25-DR-20-40-1	81	0.43	41	31.2	3.0
TXS-25-DR-20-80-1	90	0.47	45	32.1	3.1
TXS-25-DR-20-160-1	100	0.57	55	26.3	2.5
TXS-25-DR-26-10-1	95	0.20	19	28.7	2.8
TXS-25-DR-26-20-1(1)	100	0.29	28	----	---
TXS-25-DR-26-20-1(2)	100	0.26	25	25.6	2.5
TXS-25-DR-26-40-1(1)	100	0.27	26	----	---
TXS-25-DR-26-40-1(2)	100	0.28	27	25.5	2.4
TXS-25-DR-26-80-1	100	0.37	35	----	---
TXS-25-DR-26-160-1(1)	100	0.30	29	----	---
TXS-25-DR-26-160-1(2)	100	0.59	57	----	---

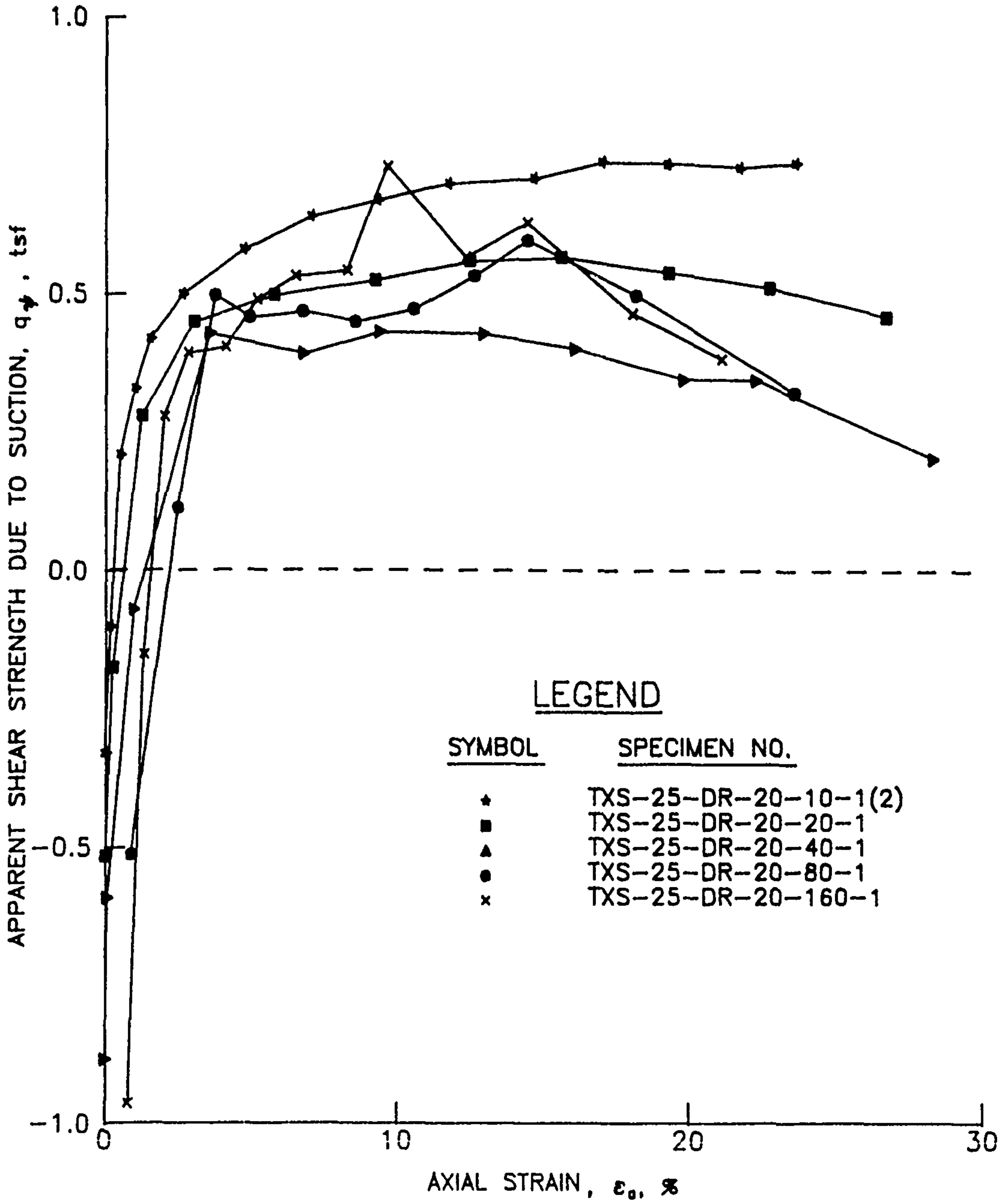

FIG. 80. Apparent shear strength due to suction for specimens of buckshot clay treated with potassium chloride prior to compaction at a nominal water content of 20 percent.

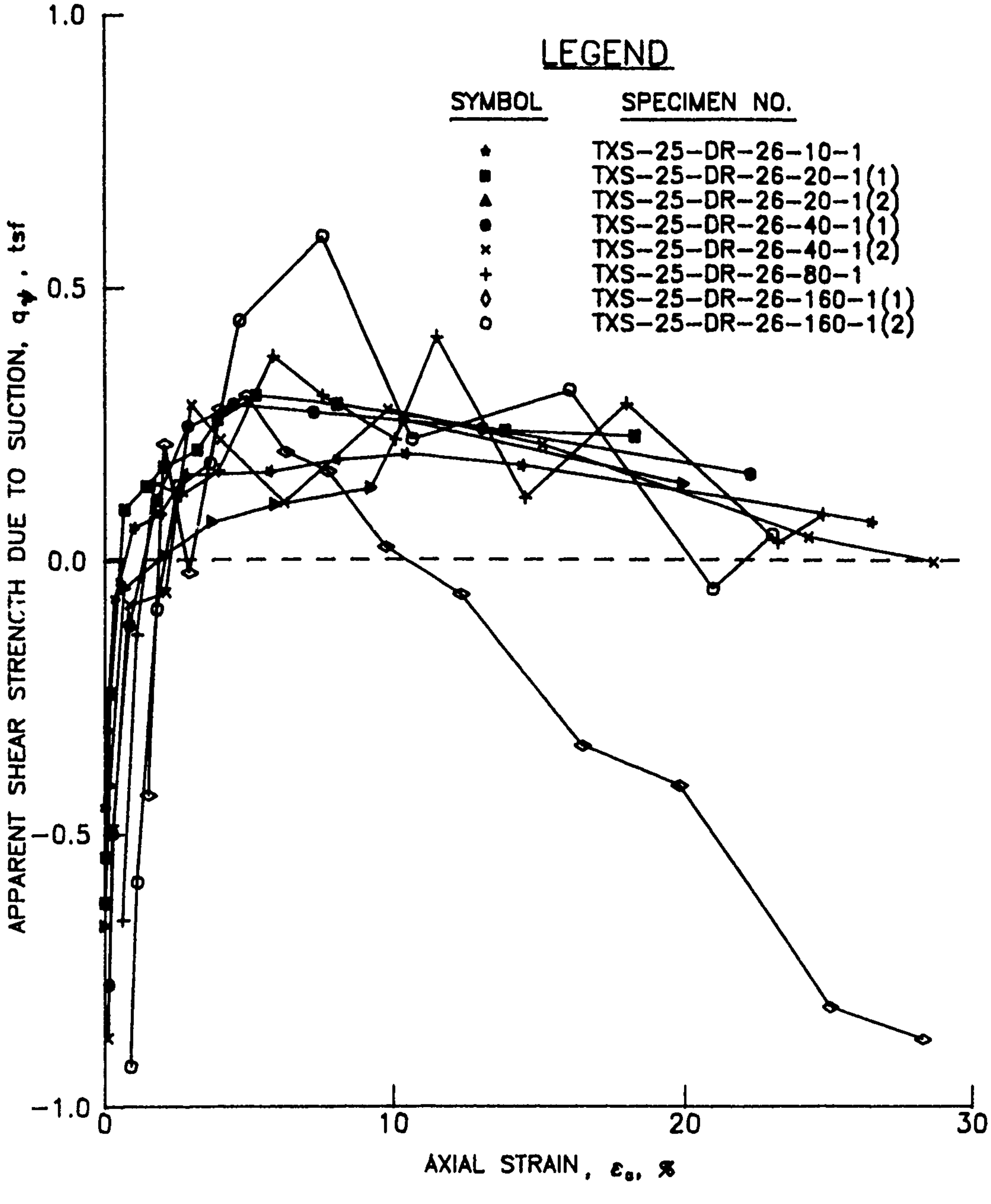

FIG. 81. Apparent shear strength due to suction for specimens of buckshot clay treated with potassium chloride prior to compaction at a nominal water content of 26 percent.

Discussion

From the data reported herein, a preliminary conclusion was obtained that the strength of unsaturated soil was dependent upon density and water content of the specimens as well as the treatment of soil with potassium chloride. For example, the influence of density may be assessed by comparing test results for specimens TXS-0-DR-20-40-4(1), TXS-0-DR-20-40-4(2) and TXS-0-DR-20-160-16. These specimens were sheared against an applied stress, (σ_3 - u), of 0.7 tsf (70 kPa), the compaction water contents were about 19.5 percent and the values of suction at failure were approximately 4 tsf (380 kPa). The void ratios at failure decreased from 0.7 for specimens TXS-0-DR-20-40-4(1) and TXS-0-DR-20-40-4(2) to 0.6 for TXS-0-DR-20-160-16. The shear strengths were 2.3, 2.4 and 3.4 tsf (220, 230 and 330 kPa), respectively. However, when the effects of density were normalized, the apparent shear strengths due to suction were approximately 0.85 tsf (80 kPa) for these three specimens. The effects of water content on the shear strengths of unsaturated specimens may be assessed by comparing the results of tests on specimens TXS-0-DR-20-10-1 and TXS-0-DR-26-10-1. For these specimens, the void ratios at failure were similar. The shear strength for specimen TXS-0-DR-20-10-1 was 2.1 tsf (200 kPa) as compared to 0.9 tsf (90 kPa) for TXS-0-DR-26-10-1. The effects of treatment of buckshot clay with potassium chloride were demonstrated by comparing the results of tests on untreated specimen TXS-0-DR-20-80-1 and treated specimen TXS-25-DR-20-80-1. For these specimens, the compaction water contents and the void ratios at failure were similar. The shear strength at failure for the treated specimen was approximately 4.6 tsf (440 kPa) as compared to 3.9 tsf (370 kPa) for the untreated specimen.

Measured values of suction were examined for quantitative or qualitative relationships to describe the influence of matrix suction on the strength of buckshot clay. These data are summarized in Tables 5 and 6 for specimens compacted at water contents of 20 and 26 percent, respectively. Linear regression analyses were conducted to evaluate the influence of suction on the apparent shear strength due to suction. The coefficients of correlation were poor, which indicated the values of the apparent shear strength due to suction were not linearly related

to suction. As can be seen from the data in these tables, the effectiveness or efficiency of suction, expressed as the arctangent of the quantity of the apparent shear strength due to suction divided by (matrix) suction, arctangent $[q_\psi/h_t]$, generally increased as saturation increased and suction decreased. At degrees of saturation less than 80 percent, large values of suction were measured although the efficiency of suction was small, i.e. the value of arctangent $[q_\psi/h_t]$ was about 5 deg. As the degree of saturation increased to about 90 percent due to consolidation, the measured values of suction decreased although the efficiency of suction increased to about 15 deg. For degrees of saturation in excess of approximately 90 percent, suction measurements were small and lacked the accuracy needed to evaluate the unsaturated strength parameter, arctangent $[q_\psi/h_t]$.

Based upon an assessment of data obtained during this investigation, it seemed as though the efficiency of matrix suction was a variable relationship, similar to Bishop's χ factor versus degree of saturation relationship. For conditions when suction was large, i.e. at low degrees of saturation, the efficiency of suction was small. At higher degrees of saturation, the efficiency of suction was larger, although smaller values of suction were measured. However, the remarkable observation was that the apparent shear strengths due to suction were nearly constant for a range of measured values of suction provided the degree of saturation at failure was less than approximately 90 percent, the water contents of the unsaturated specimens were comparable and the differences of density of the specimens had been normalized. Assuming this observation could be validated with test results published in the literature, the shear strengths of unsaturated soils could be predicted for a range of specimen conditions without the measurement of suction.

The results of tests on soil treated with potassium chloride were examined for the influence of solute suction. Although the effects could not be evaluated with a great deal of confidence because the number of tests was very limited, a comparison of the strength and deformation characteristics of treated and untreated specimens yielded sufficient information to permit a qualitative assessment of the effects

of solute suction. Pertinent observations are discussed in the following paragraphs.

The void ratio versus applied stress relationship for treated specimen 1D-18-DR-20.0, which is presented in Figure 36, was qualitatively similar to the consolidation characteristics for untreated specimens 1D-00-DR-19.0 and 1D-00-DR-22.1, which are presented in Figures 31 and 32, respectively. Similarly, the consolidation relationship for treated specimen 1D-18-DR-28.0, which is presented in Figure 35, was qualitatively similar to the consolidation characteristics of specimen 1D-00-DR-25.4, which is presented in Figure 30. A comparison of the data for all specimens indicated that water content influenced the consolidation characteristics of unsaturated soil, regardless of the treatment of the soil with potassium chloride. This observation inferred that the shear strengths of treated specimens were also dependent upon the water content of the unsaturated specimen at failure.

A comparison of the consolidation characteristics of treated specimen 1D-18-DR-20.0 and untreated specimens 1D-00-DR-19.0 and 1D-00-DR-22.1 indicated quantitative differences. This observation inferred that the apparent shear strength due to matrix suction plus solute suction for treated specimens was perhaps different than the apparent shear strength due to matrix suction for untreated specimens.

A comparison of the apparent shear strengths due to solute suction for treated specimens compacted wet and dry of optimum water content indicated that specimens compacted wet of optimum were weaker than specimens compacted dry of optimum. For specimen TXS-25-DR-20-160-1, which had been compacted at a water content of 20 percent and consolidated to a degree of saturation of approximately 100 percent prior to shear, the apparent shear strength due to suction was 0.5 tsf (50 kPa). The apparent shear strengths due to suction for five specimens which had been compacted at a water content of 26 percent and consolidated to a degree of saturation of 100 percent by applied stresses of 2.9, 5.8 or 11.5 tsf (0.28, 0.55 or 1.10 MPa) were 0.3 tsf (30 kPa). Two explanations for the differences of the apparent shear strength due to suction were considered: (a) the weight of potassium chloride used to

treat the soil and (b) the effects of testing the specimens too rapidly.

Initially, the test data inferred that the apparent shear strengths due to solute suction were dependent upon the weights of potassium chloride used to treat the soil. The weight of KCl used to treat specimen TXS-25-DR-20-160-1 was 5.0 grams as compared to 6.6 grams used to treat the specimens compacted at a water content of 26 percent. However, reexamination of the literature indicated that although different weights of KCl had been used to treat these specimens, the calculated values of solute suction were similar and therefore the apparent shear strengths due to suction should be similar.

The effects caused by shearing the unsaturated soil specimens too rapidly were then considered. Following the logic used for analyzing the test results for untreated specimens compacted at a water content of 26 percent, it is possible the pore pressures which were induced during shear had not dissipated completely. Consequently, the applied stresses, $[(\sigma_1 - u) + (\sigma_3 - u)]/2$, were different than the assumed condition of $u = 0$. It was concluded that the apparent shear strengths due to solute suction for treated specimens compacted at a water content of 26 percent and tested at a degree of saturation of 100 percent should be increased 0.1 to 0.2 tsf (10 to 20 kPa) to 0.5 tsf (50 kPa).

Based upon the decision that the apparent shear strength due to solute suction was approximately 0.5 tsf (50 kPa), specimens TXS-25-DR-20-10-1(2) and TXS-25-DR-20-20-1 were examined for the influence of matrix suction on the strengths of treated specimens. The data inferred that the maximum value of the apparent shear strength due to matrix suction for treated specimens was approximately 0.1 to 0.2 tsf (10 to 20 kPa) as compared to 0.8 to 0.9 tsf (80 to 90 kPa) for untreated specimens. Although the results were not conclusive because of a limited number of tests, these observations were consistent with the data from consolidation tests which indicated that the influence of matrix suction was quantitatively less for treated specimens than for untreated specimens.

The previous discussions have indicated that matrix suction and solute suction affect the engineering behavior of unsaturated soil.

The influence of matrix suction on the apparent shear strength due to suction was dependent upon the degree of saturation of the specimens whereas the influence of solute suction was a constant for a given concentration of salt in the pore fluid. These conclusions are consistent with data reported by Peter (1979); Richards, Emerson and Peter (1986); and Richards, Peter and Martin (1984). These researchers have reported that the engineering behavior of unsaturated soils is dependent upon the matrix and solute suction components of total suction.

MODEL AND PERFORMANCE

Interpretation of Test Results

The data presented in Tables 5 and 6 and Figures 70 through 77 indicated that matrix suction in unsaturated soil produced the same effect as increasing the value of cohesion in a Mohr-Coulomb strength relationship provided that density differences between saturated and unsaturated specimens were insignificant or had been normalized, such as for the investigation reported herein. This observation inferred that shear strengths of unsaturated soils, i.e. degrees of saturation less than approximately 85-90 percent, could be expressed by a modified Mohr-Coulomb strength relationship as:

$$\tau = c' + (\sigma - u_a) \tan \phi' + C_\psi \tag{35}$$

where

τ = shear strength

$(\sigma - u_a)$ = applied stress

c' = cohesion intercept evaluated in the conventional manner for saturated soils

ϕ' = angle of shearing resistance evaluated in the conventional manner for saturated soils

C_ψ = apparent cohesion due to suction

Preliminary assessment of data for the investigation reported herein appeared to be inconsistent with the results reported by Ho and Fredlund (1982a) and Chantawarangul (1983). These researchers reported that the apparent shear strengths due to suction for unsaturated soils increased linearly as matrix suction increased whereas the strengths for the unsaturated soils reported herein were not linearly dependent upon changes of suction. The most obvious explanation for these differences was test type. Ho and Fredlund (1982a, 1982b) conducted consolidated drained (CD) tests on unsaturated specimens of decomposed granite and decomposed rhyolite; the water contents as well as the densities of these specimens were allowed to change during the tests.

Constant water content (CW) tests were conducted for the investigation reported herein; the water content of the specimens was held constant although the density of the specimens was permitted to vary as the tests were conducted.

To check the validity of the shear strength model proposed in Equation 35, CW test results from other studies of unsaturated soil behavior were reanalyzed. Bishop, Alpan, Blight and Donald (1961) reported the results for unsaturated specimens of compacted boulder clay. These data are illustrated in Figures 82a and 82b and summarized in Table 8. From the curve identified as $[(\sigma_1 + \sigma_3)/2 - u_a]$ in Figure 82a, the failure strength can be approximated as two linear segments for tests 1 through 4 and tests 5 through 9 with a curvilinear segment connecting tests 4 and 5. From the data presented in Figure 82b, tests 1 through 5 have degrees of saturation less than 90 percent while tests 6 through 9 have degrees of saturation greater than 90 percent.

Aided by Fredlund's (1979) guidance that air becomes occluded at degrees of saturation in excess of 85 to 90 percent and by the shape of the failure envelope presented in Figure 82a, the strength increase due to suction for tests 1 through 4 or tests 1 through 5 was examined and found to be approximately 9 psi (0.6 tsf or 60 kPa). Linear regression analyses were conducted to evaluate the influence of suction on the shear strengths of the unsaturated soil specimens. Results are summarized in Table 8. When the degree of saturation at failure was less than 90 percent, such as for tests 1 through 4 or tests 1 through 5, the coefficient of correlation was poor, i.e. $-0.5 < r < 0.5$. A regression analysis was also conducted on tests 1 through 9. The results indicated that $r = 0.975$ and $\phi^b = 22.4$ deg; these values agree with $r = 0.974$ and $\phi^b = 21.7$ deg which are reported in Table 2 (after Ho and Fredlund, 1982a). However, tests 6 through 9 had degrees of saturation in excess of 90 percent and probably should not be included in an analysis of the ϕ^b parameter.

The U.S. Bureau of Reclamation has conducted numerous studies of the shear strengths of unsaturated soils. Results of two studies were

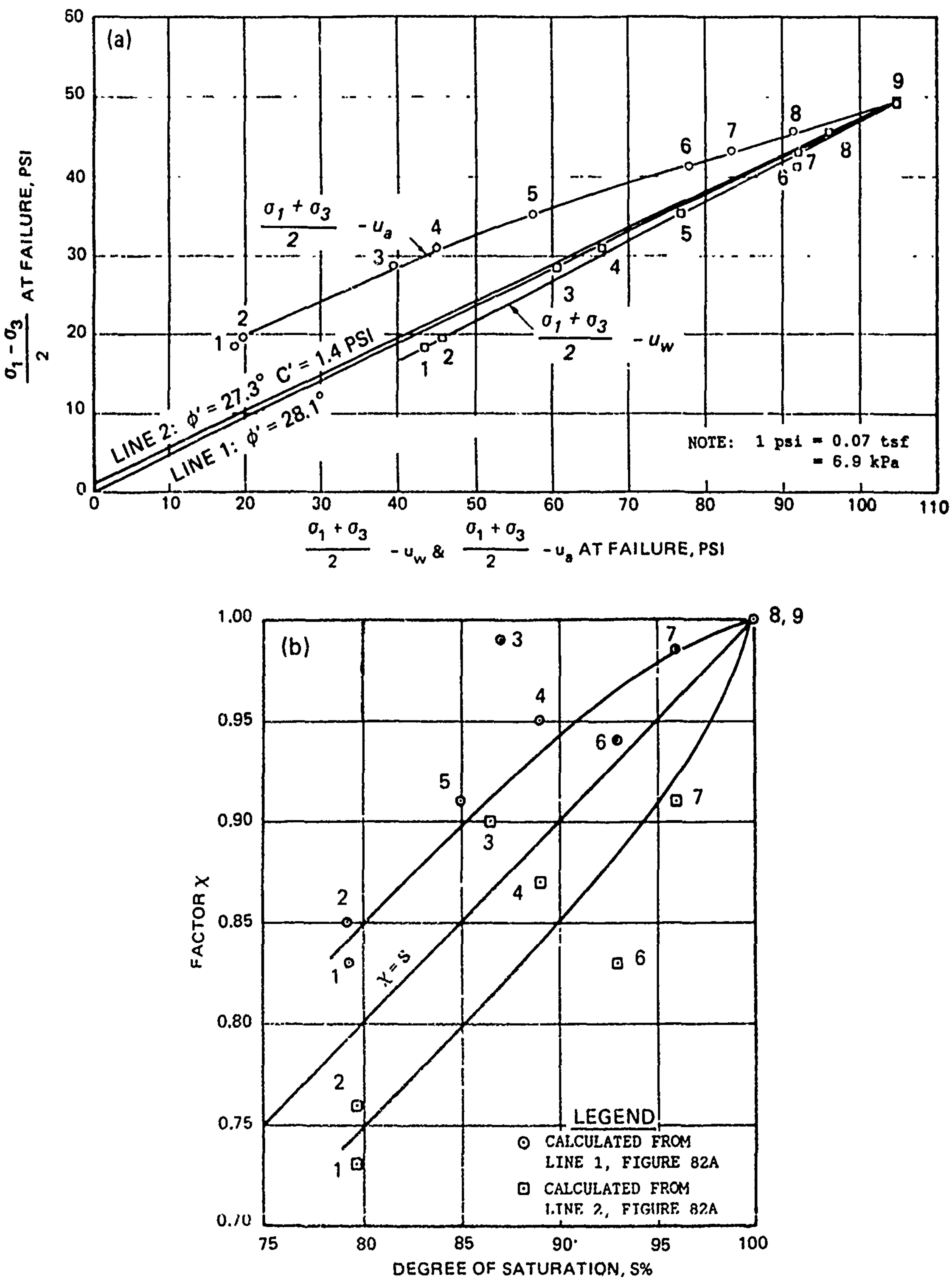

FIG. 82. Triaxial tests on a boulder clay compacted and sheared at a constant water content of 11.6 percent (After Bishop, Alpan, Blight and Donald, 1961). (a) Shear strengths of unsaturated specimens. (b) Relationship of degree of saturation and factor χ for unsaturated specimens.

Table 8. Summary of Shear Strengths of Unsatur
(After Bishop, Alpan, Blight an

Test* No.	Shear Stress $\left[\frac{\sigma_1 - \sigma_3}{2}\right]$ psi**	Normal Stress $\left[\frac{\sigma_1 + \sigma_3}{2} - u_a\right]$ psi	Normal Stress $\left[\frac{\sigma_1 + \sigma_3}{2} - u_w\right]$ psi	Matrix† Suction $[u_a - u_w]$ psi	Calcu-lated†† Shear Stress $\left[\frac{\sigma_1 - \sigma_3}{2}\right]$ psi	Apparent‡ Shear Strength Due to Suction $\delta\left[\frac{\sigma_1 - \sigma_3}{2}\right]$ psi	Calcu-lated‡‡ χ-Factor
1	18.5	18.7	43.6	24.9	9.8	8.7	0.76
2	19.6	19.9	45.8	25.9	10.4	9.2	0.78
3	28.6	39.6	60.6	21.0	19.4	9.2	0.95
4	31.1	45.0	66.7	21.7	21.9	9.2	0.93
5	35.3	57.5	76.7	19.4	27.6	7.7	0.87
6	41.4	77.8	91.8	14.0	36.9	4.5	0.70
7	43.3	83.3	92.1	8.8	39.5	3.8	0.95
8	45.8	91.5	96.1	4.6	43.2	2.6	1.22
9	49.2	104.8	104.8	0.0	49.3	-0.1	----

* For test numbers and test data refer to Figures 82a and 82b.
** 1.0 psi = 0.072 tsf = 6.9 kPa.

† $[u_a - u_w] = \left[\frac{\sigma_1 + \sigma_3}{2} - u_w\right] - \left[\frac{\sigma_1 + \sigma_3}{2} - u_a\right]$

†† The calculated shear stress refers to the shear strength at failure as determined from
c′ = 1.4 psi and ϕ′ = 27.3 deg.

‡ The apparent shear strength is the difference between the strength of the unsaturated
strength for a saturated specimen.

‡‡ $\chi_{calculated} = \frac{\delta\,[(\sigma_1 - \sigma_3)/2]}{(u_a - u_w)\tan\phi'\cos\phi'}$ is based upon the shear strength parameters c′ = 1

\# Obtained from Figure 82b for saturated strength parameters c′ = 1.4 psi and ϕ′ = 27.3

\## The calculated value is based upon saturated strength parameters c′ = 0 psi and ϕ′ = 2

§ Obtained from Figure 82b for saturated strength parameters c′ = 0 psi and ϕ′ = 28.1 de

hs of Unsaturated Specimens of Boulder Clay
n, Blight and Donald, 1961)

t‡ h n	Calcu-lated‡‡ χ-Factor	Meas-ured# χ-Factor	Calcu-lated## χ-Factor	Meas-ured§ χ-Factor	Saturation at Failure	Regression Analyses for Apparent Shear Strength Due to Suction: Test No.	Inter-cept	Slope	Coefficient of Correlation
3]					S				r
					%		psi		
	0.76	0.73	0.83	0.83	79				
	0.78	0.76	0.84	0.85	79				
	0.95	0.90	1.00	0.99	87				
	0.93	0.87	0.97	0.95	89				
	0.87	----	0.90	0.91	85				
	0.70	0.83	0.72	0.94	93				
	0.95	0.91	0.98	0.98	96				
	1.22	----	1.24	1.00	100				
	----	----	----	----	100				
						1-4	10.1	-0.044	-0.425
						1-5	6.1	0.121	0.507
						1-9	0.4	0.366	0.975

termined from the saturated strength parameters

unsaturated specimen and the calculated shear

meters c' = 1.4 psi and ϕ' = 27.3 deg.

nd ϕ' = 27.3 deg.
si and ϕ' = 28.1 deg.
ϕ' = 28.1 deg.

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reanalyzed using Equation 35 and are summarized in Table 9. Richmond (1978) reported a study of compacted specimens of sandy clay. The apparent shear strength due to suction was 0.5 tsf (50 kPa). The coefficient of correlation for the influence of suction on the shear strength was determined as r = -0.35. Prizio (1979) reported a similar study for compacted specimens of sandy silt. The apparent shear strength due to suction was 0.4 tsf (40 kPa). A regression analysis to evaluate the influence of suction on shear strength was not appropriate because suction remained nearly constant for the range of test conditions which specimens had been subjected.

Lam (1980) reported a study using compacted specimens of decomposed rhyolite from Hong Kong. Results are summarized in Table 10. Although the soil was classified as a CH clay based upon Atterberg limits, the engineering properties were similar to the engineering properties of a silt (Lumb, 1965). For specimens compacted to a dry density of 97 pcf (1520 kg/m^3) at a water content of 25 percent, the apparent shear strength due to suction was 0.9 tsf (90 kPa). For specimens compacted to a dry density of 92 pcf (1470 kg/m^3) at a water content of 28 percent, the apparent shear strength due to suction was 0.4 tsf (40 kPa). Regression analyses to determine the influence of suction on the shear strengths of unsaturated soil were inconclusive because suction measurements were similar for the range of test conditions.

Townsend and Peterson (1979) reported the results of direct shear tests conducted on inundated and unsaturated specimens of an oil shale waste product. The material was a nonplastic silt derived from carbonate rocks which had been ground or crushed prior to being retorted by the TOSCO process. Results of these tests are summarized in Table 11. The apparent shear strength due to suction was 1 tsf (100 kPa). The degrees of saturation at failure for the unsaturated specimens ranged from 70 to 75 percent. Suction was not measured.

Casagrande and Hirschfeld (1960, 1962) reported studies of the shear strengths of compacted specimens of sandy clay. The test results, which are summarized in Table 12, indicated that shear strengths of unsaturated specimens were dependent upon the water content and the

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Table 9. Summary of Shear Strengths of Unsaturated Specimens of Sandy Clay (After

Soil Type	Test* Type	Conditions at Failure: Void Ratio	Water Content	Saturation	Shear Stress**		Normal Stress		Matrix Suction		(
		e	w	S	$\left[\frac{(\sigma_1 - u) - (\sigma_3 - u)}{2}\right]$		$\left[\frac{(\sigma_1 - u) + (\sigma_3 - u)}{2}\right]$		$[u_a - u_w]$		$\left[\frac{(\sigma_1}{}\right.$
			%	%	tsf	kPa	tsf	kPa	tsf	kPa	t
Sandy Clay	CU	0.434	16.0	---	3.4	320	5.4	510	---	---	-
		0.427	16.0	---	3.9	370	6.4	610	---	---	-
		0.421	15.6	---	3.3	310	5.2	500	---	---	-
		0.400	15.3	---	7.9	750	13.4	1280	---	---	-
	UU	0.443	14.1	81	4.1	390	5.8	560	0.5	50	3
		0.420	14.0	81	4.1	390	6.2	600	0.9	90	3
		0.433	14.0	83	8.0	770	13.1	1260	0.2	20	7
		0.415	14.1	89	12.1	1160	19.6	1870	0.3	30	11
Sandy Silt	CU	0.496	18.4	---	3.7	360	6.2	600	---	---	-
		0.503	18.3	---	3.8	370	6.5	630	---	---	-
	CD	0.575	22.5	---	2.2	210	3.6	350	---	---	-
		0.484	17.3	---	5.1	490	8.7	830	---	---	-
		0.417	16.2	---	10.5	1010	17.7	1700	---	---	-
	UU	0.517	13.4	67	2.8	270	4.2	400	0.14	14	2
		0.495	13.6	72	5.8	550	9.1	880	0.15	14	5
		0.461	13.4	76	10.6	1020	17.1	1640	0.16	15	10

* CU - Saturated, consolidated undrained with pore water pressure measurements.
CD - Saturated, consolidated drained.
UU - Unsaturated, unconsolidated undrained with pore air and pore water pressure measurement.
** "u" is the pore air pressure for unsaturated specimens and pore water pressure for saturated specime
† The calculated shear stress refers to the shear stress at failure for saturated specimens.
†† The apparent shear strength is the difference between the strength of the unsaturated specimen and t
saturated specimens.

ecimens of Sandy Clay (After Richmond, 1978) and Sandy Silt (After Prizio, 1979)

l Stress	Matrix Suction		Calculated† Shear Stress		Apparent†† Shear Strength Due to Suction		Shear Values Corrected for Pore Pressure			Coefficient of Correlation
$+ (\sigma_3 - u)$ / 2	$[u_a - u_w]$		$\left[\frac{(\sigma_1 - u) - (\sigma_3 - u)}{2}\right]$		$\delta\left[\frac{(\sigma_1 - u) + (\sigma_3 - u)}{2}\right]$		c'		ϕ'	r
kPa	tsf	kPa	tsf	kPa	tsf	kPa	tsf	kPa	deg	
510	---	---	---	---	---	---				
610	---	---	---	---	---	---				
500	---	---	---	---	---	---				
1280	---	---	---	---	---	---	0.4	40	34.4	0.9998
560	0.5	50	3.6	340	0.5	50				
600	0.9	90	3.8	370	0.3	30				
1260	0.2	20	7.7	740	0.3	30				
1870	0.3	30	11.3	1090	0.8	70				
600	---	---	---	---	---	---				
630	---	---	---	---	---	---				
350	---	---	---	---	---	---				
830	---	---	---	---	---	---				
1700	---	---	---	---	---	---	0.0	0	36.3	0.9999
400	0.14	14	2.5	240	0.3	30				
880	0.15	14	5.4	520	0.4	40				
1640	0.16	15	10.1	970	0.5	50				

ients.

pressure measurements.
ressure for saturated specimens.
turated specimens.
he unsaturated specimen and the calculated shear strength for

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Table 10. Summary of Saturated and Unsaturated Tests on Compacted Specimens of Decompos
(After Lam, 1980)

Test Series	Dry† Density pcf	Water† Content %	Shear Stress tsf	Shear Stress kPa	Normal Stress tsf	Normal Stress kPa	Saturated†† Strength Parameters tsf	Saturated†† Strength Parameters kPa	Saturated†† Strength Parameters deg	Apparent* Shear Strength Due to Suction tsf	Apparent* Shear Strength Due to Suction kPa	Matrix Su(tsf
CIUS-1	96	25.3	0.14	13.6	0.19	18.3	----	---	----	----	----	----
	96	25.0	0.29	28.2	0.47	44.6	----	---	----	----	----	----
	96	25.4	0.45	42.8	0.74	70.7	----	---	----	----	----	----
	96	25.6	0.74	71.3	1.35	129.3	----	---	----	----	----	----
	96	25.5	1.38	131.9	2.56	245.7	0.05	5.0	31.1	----	----	----
CIUS-2	92	21.0	0.04	4.0	0.08	8.1	----	---	----	----	----	----
	91	21.9	0.16	15.5	0.25	24.1	----	---	----	----	----	----
	92	21.8	0.32	31.1	0.59	56.8	----	---	----	----	----	----
	92	21.7	0.45	42.8	0.80	76.3	----	---	----	----	----	----
	92	21.3	1.07	102.4	2.02	193.3	0.02	1.6	31.6	----	----	----
CIUS-3	92	24.7	0.19	18.2	0.29	27.7	----	---	----	----	----	----
	91	24.5	0.22	20.8	0.36	34.5	----	---	----	----	----	----
	92	24.3	0.44	42.1	0.74	70.9	----	---	----	----	----	----
	92	24.6	0.59	56.7	1.04	100.0	----	---	----	----	----	----
	91	24.9	1.01	97.1	1.88	180.2	0.04	4.0	31.4	----	----	----
CIUS-4	91	27.9	0.19	18.2	0.31	29.9	----	---	----	----	----	----
	92	27.6	0.24	22.8	0.44	42.2	----	---	----	----	----	----
	92	27.3	0.41	38.9	0.73	70.0	----	---	----	----	----	----
	92	27.6	0.62	59.3	1.15	110.0	----	---	----	----	----	----
	92	27.5	1.07	102.8	1.99	190.4	0.01	1.4	32.1	----	----	----
CIUS-5	87	24.5	0.13	12.9	0.19	17.9	----	---	----	----	----	----
	87	24.0	0.14	13.4	0.22	21.5	----	---	----	----	----	----
	87	24.7	0.17	16.1	0.26	25.0	----	---	----	----	----	----
	87	24.2	0.29	27.8	0.50	48.3	----	---	----	----	----	----
	87	24.7	0.43	41.2	0.77	74.2	----	---	----	----	----	----
	87	23.9	0.54	51.6	0.98	94.0	----	---	----	----	----	----
	87	24.8	1.09	104.0	2.04	196.0	0.03	3.1	31.0	----	----	----
------	--	----	----	-----	----	-----	0.03	2.9	31.5	----	----	----
CIUU-1	97.1	24.5	2.05	196.4	2.16	206.8	----	---	----	0.89	85.4	2.12
	97.0	24.6	2.34	224.2	2.65	254.2	----	---	----	0.92	88.5	2.21
CIUU-6	91.4	28.0	1.10	105.8	1.21	115.7	----	---	----	0.44	42.5	1.15
	91.7	28.1	1.32	126.6	1.64	157.0	----	---	----	0.43	41.7	1.09
	92.5	27.6	1.68	160.6	2.31	221.5	----	---	----	0.44	42.0	1.11

† The dry densities and water contents of saturated specimens, identified as the "CIUS" tests ser
tial or as compacted conditions. The water contents and dry densities of unsaturated specimen
the "CIUU" test series, were the after consolidation conditions.

†† The saturated strength parameters are c′ and ϕ'.

* The apparent shear strength due to suction is the difference between the strength of a specimen
the saturated strength parameters and the strength of the unsaturated specimen.

** The unsaturated strength parameter is the apparent shear strength due to suction divided by su

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turated Tests on Compacted Specimens of Decomposed Rhyolite
(After Lam, 1980)

ress	Saturated†† Strength Parameters			Apparent* Shear Strength Due to Suction		Matrix Suction		Unsaturated Strength** Parameter
kPa	tsf	kPa	deg	tsf	kPa	tsf	kPa	deg
18.3	----	---	----	----	----	----	-----	----
44.6	----	---	----	----	----	----	-----	----
70.7	----	---	----	----	----	----	-----	----
29.3	----	---	----	----	----	----	-----	----
45.7	0.05	5.0	31.1	----	----	----	-----	----
8.1	----	---	----	----	----	----	-----	----
24.1	----	---	----	----	----	----	-----	----
56.8	----	---	----	----	----	----	-----	----
76.3	----	---	----	----	----	----	-----	----
93.3	0.02	1.6	31.6	----	----	----	-----	----
27.7	----	---	----	----	----	----	-----	----
34.5	----	---	----	----	----	----	-----	----
70.9	----	---	----	----	----	----	-----	----
00.0	----	---	----	----	----	----	-----	----
30.2	0.04	4.0	31.4	----	----	----	-----	----
29.9	----	---	----	----	----	----	-----	----
42.2	----	---	----	----	----	----	-----	----
70.0	----	---	----	----	----	----	-----	----
10.0	----	---	----	----	----	----	-----	----
90.4	0.01	1.4	32.1	----	----	----	-----	----
17.9	----	---	----	----	----	----	-----	----
21.5	----	---	----	----	----	----	-----	----
25.0	----	---	----	----	----	----	-----	----
48.3	----	---	----	----	----	----	-----	----
74.2	----	---	----	----	----	----	-----	----
94.0	----	---	----	----	----	----	-----	----
96.0	0.03	3.1	31.0	----	----	----	-----	----
---	0.03	2.9	31.5	----	----	----	-----	----
06.3	----	---	----	0.89	85.4	2.12	203.0	22.8
34.2	----	---	----	0.92	88.5	2.21	211.5	22.7
15.7	----	---	----	0.44	42.5	1.15	110.0	21.0
37.0	----	---	----	0.43	41.7	1.09	104.0	21.7
21.5	----	---	----	0.44	42.0	1.11	106.0	21.6

ed specimens, identified as the "CIUS" tests series, are the ini-
ntents and dry densities of unsaturated specimens, identified as
dation conditions.
'.
he difference between the strength of a specimen calculated from
ngth of the unsaturated specimen.
rent shear strength due to suction divided by suction.

Table 11. Summary of Direct Shear Test Results on Saturated and Unsaturated Specimens of Oil Shale Retorted by the TOSCO Process (After Townsend and Peterson, 1979)

Test Type	Shear Stress		Normal Stress		Strength* Parameters			Coefficient of Correlation	Apparent** Shear Strength Due to Suction	
	tsf	kPa	tsf	kPa	tsf	kPa	deg	r	tsf	kPa
Wet†	0.7	70	1.5	140	---	--	----	-----	---	---
	2.4	230	3.0	290	---	--	----	-----	---	---
	5.1	490	7.0	670	---	--	----	-----	---	---
	9.5	910	14.0	1340	---	--	----	-----	---	---
	1.0	100	1.5	140	---	--	----	-----	---	---
	2.1	200	3.0	290	---	--	----	-----	---	---
	4.8	460	7.0	670	---	--	----	-----	---	---
	9.9	950	14.0	1340	---	--	----	-----	---	---
	----	----	----	----	0.0	0	34.9	0.998	---	---
Dry†	2.0	190	1.5	140	---	--	----	-----	1.0	100
	2.9	280	3.0	290	---	--	----	-----	0.8	80
	6.1	580	7.0	670	---	--	----	-----	1.2	120
	11.0	1060	14.0	1340	---	--	----	-----	1.2	120
	----	----	----	----	0.9	90	36.0	0.999	---	---

† Wet specimens were inundated prior to testing while dry specimens were tested at the "as compacted" or natural water content.

* The saturated strength parameters are c' and ϕ'. For the unsaturated specimens, the strength parameters are ϕ' and $c' + C_\psi$, as given by Equation 35.

** The apparent shear strength due to suction was determined by subtracting the shear strength of a hypothetical saturated specimen, calculated from saturated strength parameters determined by regression analysis, from the strength of an unsaturated specimen.

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Table 12. Summary of Shear Strengths of Saturated and Unsaturated Spe
(After Casagrande and Hirschfeld, 1960, 1962)

Test No.	Test* Type	Water Content w %	Dry** Density γ_d pcf	Saturation S %	Shear Stress@ $\left[\frac{(\sigma_1-u) - (\sigma_3-u)}{2}\right]$ tsf	kPa	Normal Stress $\left[\frac{(\sigma_1-u) + (\sigma_3-u)}{2}\right]$ tsf	kPa	Calculated† Shear Stress $\left[\frac{(\sigma_1-u) - (\sigma_3-u)}{2}\right]$ tsf	kPa	Sh Du $\delta\left[(\sigma\right.$
R1	CU	11.9	106.0	63.2	0.5	50	0.7	70	---	---	
R2		13.2	107.1	62.4	1.2	110	1.9	180	---	---	
R3		13.6	106.0	62.6	1.3	130	2.3	220	---	---	
R4		13.4	107.7	63.7	2.3	220	4.3	410	---	---	
R5		13.6	107.2	64.0	2.6	250	5.3	510	---	---	
R6		13.5	106.6	62.3	2.6	250	4.3	410	---	---	
R7		13.7	108.0	65.5	3.6	340	6.1	580	---	---	
R8		13.3	105.8	60.2	5.7	550	11.0	1050	---	---	
R9		16.4	108.0	78.8	1.0	90	1.4	140	---	---	
R10		16.7	105.5	75.0	1.2	120	2.1	200	---	---	
R11		16.6	106.1	76.0	1.6	150	2.6	250	---	---	
R12		15.5	107.9	74.2	2.3	220	3.7	240	---	---	
R13		16.7	107.2	78.8	3.7	350	5.9	560	---	---	
R14		16.2	107.7	76.6	5.9	560	11.2	1080	---	---	
Q1	Q	13.8	105.5	62.5	2.0	190	2.6	250	1.6	150	0
Q2		13.8	105.8	62.8	2.6	250	3.9	370	2.2	210	0
Q3		13.8	106.4	63.9	4.6	450	7.1	680	3.9	370	0
Q4		13.4	104.1	59.2	5.4	520	9.2	880	4.9	470	0
Q5		13.2	104.6	57.7	7.1	680	12.2	1170	6.5	620	0
Q9	Q	16.1	105.5	73.3	1.3	120	1.7	160	1.1	110	0
Q10		16.1	106.6	74.0	2.0	200	2.9	280	1.7	170	0
Q11		16.4	106.6	76.7	2.5	240	3.9	370	2.2	210	0
R40	CU	13.3	112.9	72.1	1.2	110	1.8	170	---	---	
R41		14.3	112.7	77.5	2.6	250	4.4	420	---	---	
R42		13.4	113.3	74.0	2.6	250	4.2	400	---	---	
R43		13.1	110.8	67.2	2.0	190	3.4	330	---	---	
R44		13.1	111.2	68.3	2.8	270	4.4	430	---	---	
R45		12.5	111.9	65.9	4.1	390	6.7	640	---	---	
R46		13.2	110.0	66.4	5.8	550	10.1	970	---	---	
Q34	Q	12.9	111.1	66.8	2.8	270	3.6	350	2.2	210	0
Q35		12.8	110.9	66.1	3.8	360	5.6	530	3.3	320	0
Q36		13.0	110.8	65.3	5.5	530	9.1	870	5.3	510	0
Q37		13.1	111.6	69.0	7.4	710	12.1	1160	6.9	670	0
Q40	Q	16.3	110.7	83.8	1.3	130	1.8	170	1.2	110	0
Q41		16.7	110.4	82.9	2.0	190	2.9	270	1.8	170	0

* CU - Saturated, consolidated undrained with pore water pressure measurements.
Q - Unsaturated, unconsolidated undrained with pore air pressure measurements.
** 100 lb/ft^3 = 1600 kg/m^3
@ "u" is the pore air pressure for unsaturated specimens and pore water pressure for saturated specimens
† The calculated shear stress refers to the shear stress at failure calculated from the saturated streng
†† The apparent shear strength is the difference between the strength of the unsaturated specimen and th
saturated specimens.

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Strengths of Saturated and Unsaturated Specimens of Sandy Clay
Casagrande and Hirschfeld, 1960, 1962)

Normal Stress $\left[\frac{(\sigma_1-u) + (\sigma_3-u)}{2}\right]$		Calculated† Shear Stress $\left[\frac{(\sigma_1-u) - (\sigma_3-u)}{2}\right]$		Apparent†† Shear Strength Due to Suction $\delta\left[\frac{(\sigma_1-u) + (\sigma_3-u)}{2}\right]$		Shear Values Corrected for Pore Pressures c'		ϕ'	Coefficient of Correlation r
tsf	kPa	tsf	kPa	tsf	kPa	tsf	kPa	deg	
0.7	70	---	---	---	---				
1.9	180	---	---	---	---				
2.3	220	---	---	---	---				
4.3	410	---	---	---	---				
5.3	510	---	---	---	---				
4.3	410	---	---	---	---				
6.1	580	---	---	---	---				
11.0	1050	---	---	---	---				
1.4	140	---	---	---	---				
2.1	200	---	---	---	---				
2.6	250	---	---	---	---				
3.7	240	---	---	---	---				
5.9	560	---	---	---	---				
11.2	1080	---	---	---	---	0.3	30	30.6	0.993
2.6	250	1.6	150	0.38	36				
3.9	370	2.2	210	0.42	40				
7.1	680	3.9	370	0.79	76				
9.2	880	4.9	470	0.49	47				
12.2	1170	6.5	620	0.62	60				
1.7	160	1.1	110	0.15	15				
2.9	280	1.7	170	0.31	29				
3.9	370	2.2	210	0.28	26				
1.8	170	---	---	---	---				
4.4	420	---	---	---	---				
4.2	400	---	---	---	---				
3.4	330	---	---	---	---				
4.4	430	---	---	---	---				
6.7	640	---	---	---	---				
10.1	970	---	---	---	---	0.2	20	33.7	0.998
3.6	350	2.2	210	0.55	53				
5.6	530	3.3	320	0.49	47				
9.1	870	5.3	510	0.27	26				
12.1	1160	6.9	670	0.43	41				
1.8	170	1.2	110	0.14	14				
2.9	270	1.8	170	0.23	22				

ure measurements.
ssure measurements.

ore water pressure for saturated specimens.
ilure calculated from the saturated strength parameters c' and ϕ'.
rength of the unsaturated specimen and the calculated shear strength for

density of specimens at failure. For specimens compacted to a dry density of 106 pcf (1700 kg/m^3) and tested at water contents of 14 and 16 percent, the apparent shear strengths due to suction were approximately 0.5 and 0.2 tsf (50 and 20 kPa), respectively. For specimens compacted to a dry density of 111 pcf (1780 kg/m^3) at water contents of 13 and 16 percent, the apparent shear strengths due to suction decreased from 0.4 to 0.2 tsf (40 to 20 kPa), respectively. Suction measurements were not obtained during these investigations.

The results of unconfined compression tests (Chen, 1984) on a plastic clay from Bangkok, Thailand, were reanalyzed using Equation 35 and are reported in Table 13. These data also indicated that strengths of unsaturated specimens were dependent upon the water content and density of specimens at failure. For specimens compacted to a density of 96 pcf (1540 kg/m^3), the apparent shear strengths due to suction decreased from 1.4 to 0.7 tsf (130 to 70 kPa) as the water contents of the specimens increased from 16.5 to 19.3 percent. For specimens compacted to a density of 103 pcf (1650 kg/m^3), the apparent shear strengths due to suction decreased from 1.5 to 0.6 tsf (140 to 60 kPa) as the water contents increased from 19.0 to 23.5 percent. The effects caused by increased density are demonstrated by comparing the unconfined strengths of specimens compacted at a water content of 19 percent. As the density of specimens increased from 96 to 103 pcf (1540 to 1650 kg/m^3), the unconfined strengths increased from 0.7 to 1.5 tsf (70 to 140 kPa).

The results of unconfined compression tests on decomposed rhyolite from Hong Kong (Lam, 1980) were reanalyzed using Equation 35 and are summarized in Table 14. These data indicated that apparent shear strengths due to suction were dependent upon the water content and density of the unsaturated specimens at failure. The strength parameter due to suction, as indicated by the arctangent of the apparent shear strength due to suction divided by suction, increased from 12 to 27 deg as saturation increased from 70 to 95 percent. For saturated specimens, the angle of friction was approximately 31 deg. This response was qualitatively similar to Bishop's χ factor versus degree of saturation relationship.

Table 13. Summary of Back Pressure Saturated Tests and Unconfined Compression Tests on Compacted Specimens of Plastic Clay (After Chen, 1984)

Test* Type	Dry** Density pcf	Water Content %	Shear*** Stress tsf	Shear*** Stress kPa	Normal Stress tsf	Normal Stress kPa	Saturated Strength Parameters@ tsf	Saturated Strength Parameters@ kPa	Saturated Strength Parameters@ deg	Apparent@@ Shear Strength Due to Suction tsf	Apparent@@ Shear Strength Due to Suction kPa
CU†	-----	----	1.18	113	2.25	216	----	--	----	----	---
	-----	----	1.46	140	3.07	294	----	--	----	----	---
	-----	----	1.59	152	3.44	330	----	--	----	----	---
	-----	----	1.71	164	3.70	355	0.36	35	21.2	----	---
UC	103.0	19.0	2.88	276	----	---	----	--	----	1.48	142
	103.0	19.0	2.86	274	----	---	----	--	----	1.47	141
	103.0	20.1	2.48	238	----	---	----	--	----	1.23	117
	102.7	20.1	2.46	236	----	---	----	--	----	1.21	116
	102.7	23.5	1.55	149	----	---	----	--	----	0.63	60
	103.0	23.5	1.54	148	----	---	----	--	----	0.63	60
CU††	-----	----	0.86	82	1.56	150	----	--	----	----	---
	-----	----	0.98	93	2.12	203	----	--	----	----	---
	-----	----	1.22	117	2.67	256	0.34	33	18.7	----	---
UC	96.5	16.5	2.57	246	----	---	----	--	----	1.40	135
	96.2	16.5	2.52	242	----	---	----	--	----	1.37	131
	96.4	17.2	2.14	205	----	---	----	--	----	1.11	107
	96.6	17.2	2.17	208	----	---	----	--	----	1.13	108
	96.2	19.3	1.54	148	----	---	----	--	----	0.70	67
	96.3	19.3	1.58	151	----	---	----	--	----	0.73	70

* CU denotes consolidated undrained triaxial tests with pore pressure measurements. UC denotes unconfined compression tests.

** 100 pcf = 1600 kg/m^3

*** The shear strength of an unconfined compression test is one half of the unconfined compressive strength.

@ The saturated strength parameters are c' and ϕ'.

@@ The apparent shear strength due to suction was determined by subtracting the strength of a hypothetical specimen determined from saturated strength parameters from the shear strength of an unsaturated specimen.

† Specimens were compacted to an initial density of 102.9 pcf at a water content of 23.5 percent.

†† Specimens were compacted to an initial density of 96.7 pcf at a water content of 19.3 percent.

Table 14. Summary of Unconfined Compression Tests on Compacted Specimens of Decomposed Rhyolite (After Lam, 1980)

Test Series	Conditions at Failure: Dry* Density pcf	Water Content %	Saturation %	Unconfined Strength tsf	Unconfined Strength kPa	Apparent Shear Strength Due to Suction** tsf	Apparent Shear Strength Due to Suction** kPa	Suction tsf	Suction kPa	Unsaturated Strength Parameter† deg
UC-1-95	97.0	25.8	94	4.00	383	0.93	89	1.80	173	27.1
UC-1-90	95.7	25.0	88	3.89	373	0.90	86	2.60	249	19.1
UC-1-85	96.6	23.0	83	4.53	434	1.05	101	2.90	278	19.9
UC-1-80	96.6	21.9	79	4.47	429	1.04	100	3.16	303	18.2
UC-2-95	93.8	27.9	94	2.55	244	0.57	55	1.23	118	25.1
UC-2-90	91.3	28.0	89	2.39	229	0.54	52	1.23	118	23.7
UC-2-85	90.8	26.4	83	2.74	263	0.63	60	1.53	147	22.2
UC-2-80	91.1	24.8	78	2.94	282	0.67	64	2.23	214	16.8
UC-2-75	90.4	24.0	75	2.68	257	0.61	58	2.30	220	14.9
UC-3-95	85.8	32.6	91	1.25	120	0.27	26	0.59	57	24.3
UC-3-90	86.3	31.3	88	1.20	115	0.26	25	0.63	60	22.3
UC-3-85	86.2	29.8	84	1.51	145	0.33	32	0.91	87	20.0
UC-3-80	86.3	28.3	80	1.40	134	0.30	29	0.94	90	17.9
UC-3-75	86.5	26.3	75	1.55	149	0.34	33	1.39	133	13.8
UC-3-70	86.8	24.9	71	2.18	209	0.49	47	2.31	221	12.0

* 100 pcf = 1600 kg/m^3

** The apparent shear strength due to suction was determined by subtracting the strength of a hypothetical specimen calculated from the strength parameters for all saturated specimens reported in Table 10 from the unconfined strength of an unsaturated specimen. For example, the unconfined strength for specimen UC-1-95 was reported as 4.00 tsf (383 kPa). Since the specimen was unconfined, the shear stress and normal stress were equal to one half of the unconfined strength or 2.00 tsf (192 kPa). Using the strength parameters for saturated specimens of decomposed rhyolite which were reported in Table 10, i.e. c' = 0.03 tsf (2.9 kPa) and ϕ' = 31.5 deg, and Equations 23, 24 and 25 which relate the saturated strength parameters c' and ϕ' to a and α, the calculated shear strength for a saturated specimen was 1.07 tsf (103 kPa). The apparent shear strength due to suction was the numerical difference between the strength of an unsaturated specimen and a comparable saturated specimen, or 0.93 tsf (89 kPa).

† The unsaturated strength parameter is the arctangent of the apparent shear strength due to suction divided by suction.

Murthy, Sridharan and Nagaraj (1987) reported the results of constant water content tests which were conducted on compacted specimens of kaolin and red earth. The test results are summarized in Table 15. Specimens of kaolin were compacted to a dry density of 101 pcf (1620 kg/m^3) at a water content of 23 percent. Specimens of red earth, a low plasticity clay, were compacted to a dry density of 106 pcf (1700 kg/m^3) at a water content of 16.5 percent. After compaction, specimens were placed in desiccators containing selected concentrations of sulphuric acid and were allowed to equilibrate. The results of tests on specimens of kaolin indicated the friction angle was 33 deg and the cohesion intercept, which included the c′ and C_ψ parameters given in Equation 35, ranged from 3.1 tsf (290 kPa) at a degree of saturation of 24 percent to 4.2 tsf (400 kPa) at a degree of saturation of 87 percent to 0.6 tsf (60 kPa) at a saturation of 96 percent. The results of tests on specimens of red earth indicated the friction angle was approximately 39 deg. The cohesion intercept ranged from 5.8 tsf (560 kPa) at a degree of saturation of 12 percent to 6.6 tsf (630 kPa) at a saturation of 40 percent to 0.8 tsf (80 kPa) at a saturation of 77 percent. To provide a reference for evaluating the strengths of unsaturated specimens, tests on saturated specimens were also conducted. Unfortunately, the specimens swelled upon inundation and a valid comparison of the strengths of saturated and unsaturated specimens could not be obtained.

Discussion

From the data presented in Tables 8 through 15, it was evident that shear strengths of unsaturated specimens could be evaluated by Equation 35. The data indicated that the strengths of unsaturated soils were dependent upon the water content and the density of the specimens. The density affected the strength parameters c′ and ϕ' whereas the water content affected the apparent shear strength due to suction, C_ψ or q_ψ. The results also indicated the apparent shear strengths due to suction could be treated as a constant for a range of

Table 15. Summary of Shear Strengths of Unsaturated Specimens of Compacted Kaolinite and Compacted Red Earth (After Murthy, Sridharan and Nagaraj, 1987)

Soil Type	Initial Conditions				Cohesion* Intercept		Angle of Friction
	Dry Density		Water Content	Degree of Saturation			
	pcf	kg/m^3	%	%	tsf	kPa	deg
Kaolinite	101	1620	5.6	24	3.07	3.00	33.4
			17.9	77	3.44	3.36	33.7
			20.2	87	4.17	4.07	33.3
			21.9	94	2.56	2.50	33.3
			22.3	96	0.61	0.60	33.4
Red Earth	106	1700	2.6	12	5.8	5.7	39.2
			8.5	40	6.6	6.4	38.3
			12.8	60	4.4	4.3	38.3
			15.2	71	1.0	1.0	39.5
			16.5	77	0.8	0.8	39.0

* This value includes apparent cohesion for saturated specimens and apparent shear strength due to suction for unsaturated specimens, i.e. $c' + C_\psi$, as given by Equation 35.

normal stresses, $[(\sigma_1 + \sigma_3)/2 - u_a]$, provided the water content of the unsaturated specimens remained constant.

These observations, used in conjunction with a knowledge of the empirical relationships of water content and suction (Croney and Coleman, 1961; Johnson, 1974a, 1974b; Olson and Langfelder, 1965; Snethen and Johnson, 1980; Snethen, Johnson and Patrick, 1977), provided the continuity for comparing CW and CD test results. The correlation between suction and the apparent shear strength due to suction, as reported by Ho and Fredlund (1982a), merely reflected the influence of water content on the apparent shear strength due to suction, as reported for this investigation. As the water content of the CD test was changed, the q_ψ or C_ψ parameters also changed. Hence, Equation 35 can be used to analyze the results of CW or CD tests conducted on unsaturated soils.

It is assumed that Equation 35 is also valid for evaluating the shear strengths of unsaturated specimens as influenced by solute suction, although specific studies to assess the influence of solute suction on the shear strengths of unsaturated soils were not identified during a search of the literature. It is surmised that the effects of solute suction could be incorporated into Equation 35 as the apparent cohesion due to suction, C_ψ. To apply the equation, it is suggested that the influence of matrix suction should be evaluated at the water content and solute suction of interest because the results of this study as well as investigations by other researchers (Edil and Motan, 1984; Richards, Emerson and Peter, 1986) indicated that the influence of matrix suction was affected by solute suction.

Influence of Suction on Shear Strength

The influence of matrix suction on the shear strength of unsaturated soil was examined for possible correlations. Good correlations between the unsaturated strength parameter, arctangent $[q_\psi/h_m]$, and the degree of saturation for the data reported in Tables 5, 10 and 14 were obtained. Based upon these observations and the dependency of suction on water content, an approach for assessing the influence of matrix

suction on the shear strength of unsaturated soil was formulated. Assuming the density of the soil was known or could be estimated with reasonable confidence and provided that suction versus water content and the degree of saturation versus arctangent $[q_\psi/h_m]$ relationships were available for the soil in question, the apparent shear strength due to suction could be estimated from measured values of suction, only.

To evaluate this idea, the unconfined compression data reported in Table 14 were expressed as suction, water content, saturation and arctangent $[q_\psi/h_m]$ relationships in Figures 83a through 83d. Suction versus water content data have been presented in Figure 83a; one may observe that a good correlation exists, which is consistent with the data and observations reported by others. Saturation and water content data are presented in Figure 83c. These data have been superimposed with calculated saturation versus water content relationships for specimens compacted to dry densities of 96.5, 91.5 and 86.5 pcf (1550, 1470 and 1390 kg/m^3). Values of the unsaturated strength parameter, arctangent $[q_\psi/h_m]$, versus saturation are presented in Figure 83d. As may be observed, there is a very good correlation for these data. Although the coefficient of correlation for a linear regression analysis was 0.95, it is believed this relationship is curvilinear for most soils, as indicated by the χ factor versus degree of saturation relationships reported by Bishop, Alpan, Blight and Donald (1961); Bishop and Henkel (1962); and Bishop and Blight (1963). Suction versus arctangent $[q_\psi/h_m]$ data were plotted in Figure 83b. These data have been superimposed with curves for selected values of the apparent shear strength due to suction of q_ψ = 0.3, 0.6 and 1.0 tsf (30, 60 and 100 kPa).

To validate the proposed idea and to demonstrate the procedure for using Figure 83, test results for the second specimen in test series CIUU-1, which is presented in Table 10, were used. Enter Figure 83a with the reported value of suction of 2.21 tsf (212 kPa). The value of the water content obtained from the data in Figure 83a was 24.6 percent as compared to a measured value of 24.6 percent. Using a water content

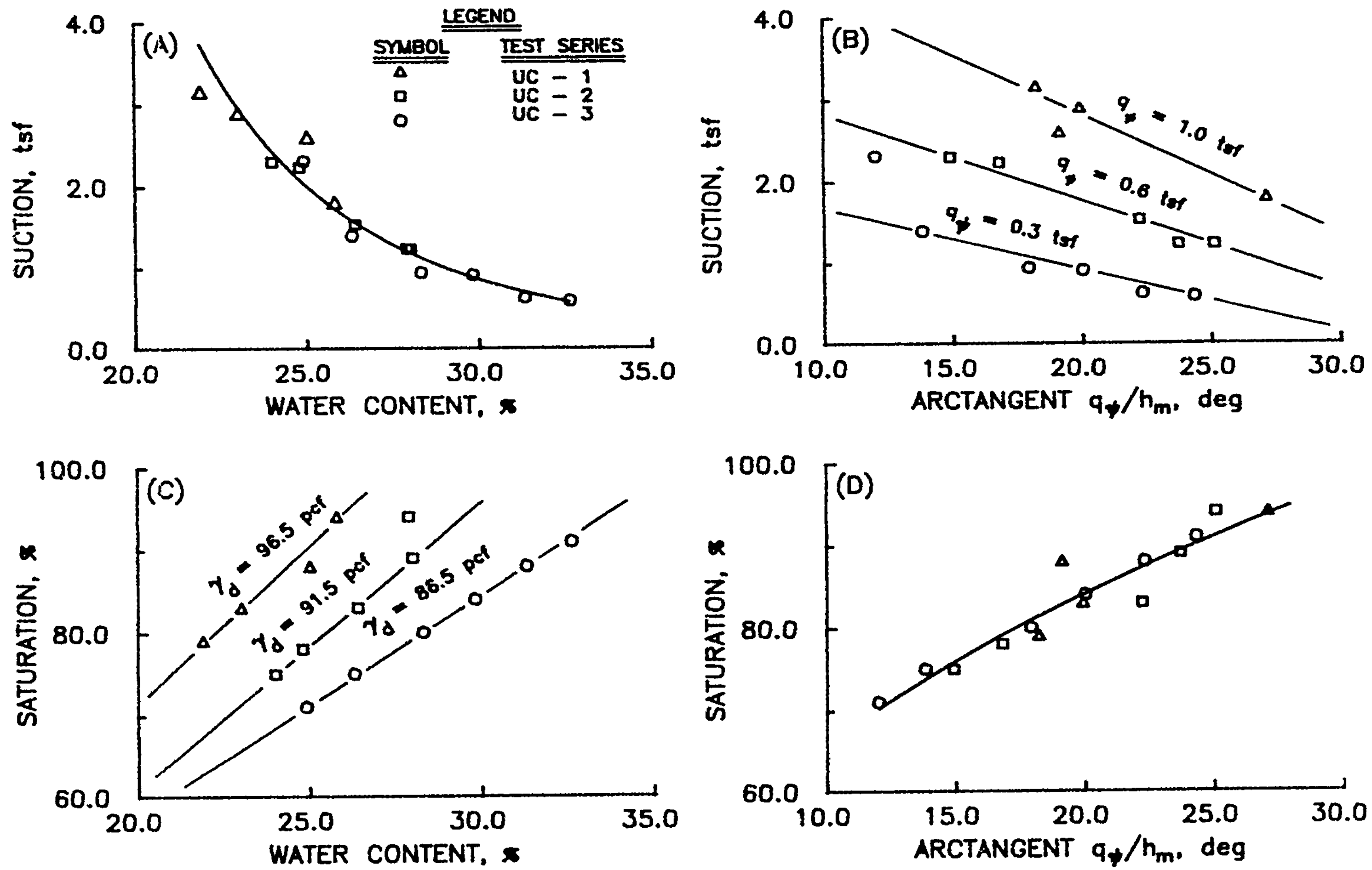

FIG. 83. Strengths of unsaturated specimens of decomposed rhyolite (After Lam, 1980). (a) Suction versus water content. (b) Apparent shear strength due to suction as a function of suction and the unsaturated strength parameter. (c) Saturation versus water content. (d) Saturation versus the unsaturated strength parameter. (1 tsf = 96 kPa; 100 lb/ft^3 = 1600 kg/m^3)

of 24.6 percent, enter Figure 83c and intersect the density curve identified as 96.5 pcf (1550 kg/m^3). The density for this specimen was reported as 97.0 pcf (1550 kg/m^3). From Figure 83c, the degree of saturation was estimated as 89 percent as compared to the reported value of 90 percent. Using a saturation of 89 percent, enter Figure 83d. A value for the unsaturated strength parameter was determined as 23.0 deg as compared to a value of 22.7 deg from Table 10. For the last step, enter Figure 83b with a value of suction of 2.21 tsf (212 kPa) and a value for the unsaturated strength parameter of 23.0 deg. These values intersect at an apparent shear strength due to suction of 0.94 tsf (90 kPa). The calculated value presented in Table 10 was 0.92 tsf (88 kPa). Estimated values of the apparent shear strength due to suction obtained from the relationships presented in Figure 83 were compared with the actual values for the other "CIUU" tests reported in Table 10. Estimated and actual values compared well.

From the data presented in the example given in Figure 83, it was evident that the apparent shear strengths due to suction were dependent upon the density and the water content of the unsaturated specimens, which is consistent with the conclusions reported herein. Furthermore, these data demonstrated that suction was a variable which was dependent on the water content of the specimen and perhaps slightly dependent upon the density of the specimen. As the water content or degree of saturation of the unsaturated specimen increased, the value of matrix suction decreased although its efficiency increased, which is consistent with Blight's (1967) explanation of the χ factor. It should be noted that Fredlund's method for estimating the shear strengths of unsaturated soils, i.e. the extended Mohr-Coulomb strength relationship, does not directly allow for a variation of the unsaturated strength parameter as the degree of saturation changes.

Although specific studies of the influence of matrix and solute suctions on the shear strengths of unsaturated soils were not identified during a search of the literature, an investigation of the influence of suction on the deformation of a Pleistocene clay (Peter, 1979) indicated the effects of solute suction were qualitatively and quantitatively similar to the effects of matrix suction. This observation

inferred that solute suction as well as matrix suction could affect the shear strengths of unsaturated clay soils. Consequently, it is believed that an approach similar to the method presented in Figure 83 could be developed to assess the influence of combinations of matrix and solute suctions on the shear strengths of unsaturated soils.

Based upon published data as well as test results obtained during this investigation, it is anticipated that the effects of solute suction should be constant for a particular ionic concentration while the effects of matrix suction could be qualitatively and/or quantitatively influenced by the type of salt in the pore fluid and its concentration. For those soils in which the engineering behavior could be affected by matrix and solute suctions, changes of the water content of the unsaturated specimen could tend to alter the concentration of salt in the pore fluid as well as the degree of saturation of the specimen. Therefore, an evaluation of the apparent shear strengths due to matrix suction and to solute suction would be necessary for the changed conditions.

Summary

As a result of this investigation, a modified Mohr-Coulomb strength relationship, given as Equation 35, has been proposed. The advantage of Equation 35 as compared to Equation 11, which was proposed by Bishop, or Equation 15, which was proposed by Fredlund, is that measurements of suction are not required to apply the model.

To apply Equation 35, cohesion, c', and the angle of friction, ϕ', should be evaluated by conventional tests on saturated specimens. The magnitude of the apparent shear strength due to matrix suction is dependent upon the water content of the specimen at failure. At full saturation the apparent shear strength due to suction would be zero, pore water pressure would be equal to the pore air pressure, and Equation 35 would revert to the conventional Mohr-Coulomb strength relationship for saturated soils. As the water content of the soil was decreased slightly from full saturation, the strength due to suction

would likely increase, provided that differences of density for saturated and unsaturated specimens were insignificant. As drying of the specimen continued, the apparent shear strength due to suction could increase or decrease, as inferred by the data presented in Table 15.

To apply the model given as Equation 35, a sufficient number of tests should be conducted on saturated specimens compacted to the desired density to obtain the saturated strength parameters. To evaluate the apparent shear strength due to suction, strength tests must be conducted on one or two unsaturated specimens which have been compacted to a density comparable to the density of the saturated specimens at a water content of interest. Similar procedures could be used for assessing the strengths of undisturbed specimens or specimens which had been treated with a salt, although it would be necessary to ensure that replicate specimens were being tested.

Only two limitations of the proposed unsaturated strength model have been identified:

(a) The shear strengths of saturated and unsaturated specimens must be compared at similar void ratios and applied stresses. If this is not possible because of significant differences of the consolidation characteristics of saturated and unsaturated specimens, a procedure similar to the normalizing technique reported herein must be employed to negate the differences of density between saturated and unsaturated specimens before the apparent shear strengths due to suction can be evaluated.

(b) Equation 35 should not be used to analyze test results for unsaturated specimens tested at high degrees of saturation, i.e. saturation greater than approximately 90 percent. Although the data which is presented in Figure 82a (tests 6-9) indicated a smooth transition from the unsaturated to the saturated state, additional studies are needed to evaluate the shear strengths of unsaturated soils at high degrees of saturation and to assess unsaturated strength models.

If unsaturated shear strengths must be characterized by soil suction, such as for an evaluation of the stability of excavations during construction operations, Equation 35 is valid. The apparent shear

strengths due to matrix suction may be evaluated using suction measurements, a suction versus water content relationship, and a saturation versus the influence of suction relationship for the soil in question, similar to the procedure suggested for the data presented in Tables 10 and 14 and Figure 83. Evaluation of the saturated strength parameters would remain identical to the procedures suggested when suction measurements were not obtained.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Conclusions drawn as a result of this study using compacted specimens of Vicksburg buckshot clay as well as tests on unsaturated soils reported in the literature follow:

(a) Based upon this investigation, the shear strengths of unsaturated soils were affected by the density and the water content of the specimens at failure. The data suggested that the angle of friction was influenced by the density of the specimens whereas the apparent cohesion due to matrix suction was affected by the water content of the unsaturated specimens at failure.

(b) An assessment of the influence of matrix suction on the shear strengths of unsaturated soil was conducted. It was concluded that suction was dependent on the water content of the unsaturated soil and the efficiency of suction was dependent upon the degree of saturation of the soil.

(c) An assessment of the influence of solute suction on the shear strengths of treated specimens of buckshot clay indicated the apparent shear strength due to solute suction was a constant for a particular ionic concentration. The influence of matrix suction on the shear strengths of treated specimens was qualitatively similar to the effects of matrix suction on untreated specimens although the values of apparent shear strength due to matrix suction were smaller.

(d) A modified Mohr-Coulomb strength relationship, given as Equation 35, was proposed to predict the strengths of unsaturated soils. To apply this model, the shear strengths of saturated and unsaturated specimens are evaluated at comparable dry densities; the apparent shear strength due to suction for the unsaturated specimen is related to its water content. The advantage of this model as compared to other models, such as those proposed by Bishop or Fredlund, is that suction is not required to apply the model.

(e) Equation 35 may also be used to characterize the shear strengths of unsaturated soils by soil suction. First, a series of

tests are required to develop relationships similar to those relationships presented in Figure 83. To apply the model, a measurement of suction is obtained and the apparent shear strength due to suction is estimated from the suction, water content, saturation and the influence of suction relationships. Evaluation of the saturated strength parameters are identical to the procedures which were suggested when suction measurements were not obtained.

Recommendations

In light of the considerable lack of knowledge relative to the shear strengths of unsaturated soils, continued research is needed. Additional studies have been identified:

(a) Laboratory investigations are required to verify and better delineate the findings of this study.

(b) Research is needed to develop and improve methods and understanding of the behavior of unsaturated soils at high degrees of saturation.

(c) Investigations are needed to determine appropriate rates for conducting triaxial tests on unsaturated soils.

(d) Theoretical studies, such as those founded on principles of thermodynamics, are needed to determine a comprehensive method for interpreting the behavior of unsaturated soils.

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APPENDIX I

PHYSICAL AND MINERALOGICAL TESTS ON BUCKSHOT CLAY

APPENDIX I. PHYSICAL AND MINERALOGICAL TESTS ON BUCKSHOT CLAY

Two samples of buckshot clay, designated as specimens 1 and 2, were delivered to the Materials Analysis Group, Structures Laboratory, U.S. Army Engineer Waterways Experiment Station (WES), on 12 September 1984 with a request to determine the cation exchange capacity (CEC), exchangeable cations and the electrical conductivity of each specimen. With the exception of the conductivity test which was modified to a 2:1 water to soil mixture to obtain enough water to perform the test, tests were conducted following the methods and procedures described by Black (1965). The results follow (Bean, 1984):

Specimen No.	CEC	Exchangeable Cations meq/100 gms Na	K	Ca	Mg	Electrical Conductivity mmho/cm	Liquid Limit %	Plasticity Index %
1*	38.2	2.6	4.7	43.2	13.4	0.25	57	36
2**	35.5	18.8	38.0	33.2	10.2	4.10	59	37

* Loose uncompacted soil at a water content of approximately 27 percent.

** Portion of triaxial specimen TXS-25-DR-27-160-1(2) which had been treated with potassium chloride.

On 15 May 1985, ten soil specimens were shipped to the Mississippi Cooperative Extension Service Soil Testing Laboratory at Mississippi State University with a request to conduct a series of regular tests (Funderburg and Crouse, 1987). The pH of the specimens varied from 6.2 to 7.0 with an average value of 6.6. No organic matter was present. The test results are summarized below:

Triaxial Specimen No.	Electrical Conductivity mmho/cm	Exchangeable Cations meq/100 gms soil				Extractable Sodium meq/100 gms
		H	K	Ca	Mg	
TXS-0-DR-20-10-1	0.3	1.00	0.66	35.77	7.78	1.996
TXS-0-DR-20-160-1(2)	0.3	0.70	0.74	39.80	8.39	4.102
TXS-0-DR-27-40-1	0.3	0.90	0.68	42.52	9.25	4.102
TXS-0-DR-27-40-2-1	1.3	0.90	2.03	38.57	8.77	2.661
TXS-0-DR-27-40-2(2)	0.9	1.70	1.16	25.82	8.35	2.772
TXS-0-DR-27-160-8	0.3	0.90	0.74	35.75	11.05	3.991
TXS-25-DR-27-20-1	5.3	1.30	3.52	25.85	8.84	2.217
TXS-25-DR-27-40-1(2)	5.2	0.70	3.33	35.20	8.34	2.328
TXS-25-DR-27-80-1	4.6	0.80	3.37	35.70	8.14	4.320
TXS-25-DR-27-160-1(1)	3.6	0.80	3.44	31.68	7.98	1.774

A letter report (Faulkner, 1985) which was attached to the test results indicated that extractable sodium was determined using a 1:4 ratio of soil to normal ammonium acetate (pH of 8.5). As a result, these data included exchangeable sodium plus soil solution and could not be used with certainty in adjusting the cation exchange capacity estimations using the "sum of cations" method.

Four soil samples and one sample of potassium chloride were delivered to the Materials Analysis Group, Structures Laboratory, WES, on 4 June 1985 to determine if the treatment of Vicksburg buckshot clay with potassium chloride converted smectite to clay-mica. Two of the clay samples had been treated with KCl and two of the samples had not been treated. The triaxial specimens had been oven dried prior to conducting the X-ray diffraction (XRD) tests. The samples were identified as:

Sample No.	Description
1	Untreated soil granules at a nominal water content of 27 percent
2	Portion of treated triaxial specimen TXS-25-DR-27-160-1(2)
3	Portion of treated triaxial specimen TXS-25-DR-27-40-1(2)
4	Portion of untreated triaxial specimen TXS-0-DR-27-40-2(1)
5	Granulated potassium chloride

Tests were conducted using an X-ray diffractometer with nickel-filtered copper radiation. The sample of KCl was ground and examined by XRD as a tightly packed powder. It was determined the KCl salt was essentially pure KCl; no other mineral constituents were identified. Slides of sedimented clay-sized material (0.002 mm. equivalent spherical diameter) were prepared from each soil specimen. Slides of the clay were examined by XRD in an air dry state and again after the soil was saturated with glycerol. Results of the tests indicated the clay specimens contained smectite, clay-sized mica and kaolinite as well as quartz. Based upon the decreased intensity of the 15-Å XRD peak in the treated clay as compared to the untreated clay and the expansion of the XRD peak to 18-Å after the clay was saturated with glycerol, it was determined that the treated clay had less smectite than the untreated clay. It was also determined that more clay-mica was present in the treated clay than the untreated clay, as indicated by an increased intensity of the 10-Å XRD peak in the treated clay. It was concluded

that treatment of buckshot clay with KCl caused a partial conversion of smectite to a clay-mica material (Alvin, 1985). These findings are similar to the guidance offered by Grim (1968), who reported that a material similar to illite was produced after a smectite had been mixed with potassium chloride and dried at 110 deg C.

APPENDIX II

COMPACTION TESTS

APPENDIX II. COMPACTION TESTS

The results of kneading compaction tests on Vicksburg buckshot clay using the low compactive effort are summarized below:

Water Content	Dry Density	
%	pcf	kg/m^3
12.5	81.2	1300
12.5	86.3	1380
16.6	88.0	1410
16.7	86.3	1380
20.2	94.5	1510
20.4	94.7	1520
22.7	99.2	1590
23.2	99.5	1590
23.6	99.1	1590
24.3	98.9	1580
26.4	95.8	1530
27.4	94.1	1510
28.6	92.4	1480
31.3	85.4	1370

The results of kneading compaction tests on Vicksburg buckshot clay using the high compactive effort are summarized below:

Water Content	Dry Density	
%	pcf	kg/m^3
12.2	92.1	1480
16.0	97.4	1560
19.7	105.1	1680
23.5	100.4	1610
27.8	90.7	1450

The results of kneading compaction tests on treated Vicksburg buckshot clay using the low compactive effort are summarized below:

Water Content %	Dry Density pcf	Dry Density kg/m^3	Estimated* Osmotic Suction tsf	Estimated* Osmotic Suction kPa
12.8	84.2	1350	0.5	50
16.6	86.0	1380	0.7	60
20.0	93.7	1500	0.8	80
24.0	99.0	1590	0.9	90
27.6	94.1	1510	0.9	90
11.7	85.8	1370	1.0	100
15.4	85.4	1370	1.1	100
19.3	92.5	1480	1.1	110
22.5	98.5	1580	1.2	120
26.0	95.9	1540	1.2	120
12.1	84.0	1350	2.1	200
16.1	85.5	1370	2.7	260
19.8	92.2	1480	3.2	310
23.4	98.3	1570	3.7	350
26.6	95.4	1530	3.8	370
11.7	85.6	1370	4.2	400
15.1	85.9	1380	4.3	420
18.8	92.9	1490	4.7	450
22.3	98.5	1580	5.1	480
25.7	96.1	1540	5.0	480
12.6	86.5	1390	15.8	1520
16.5	88.9	1420	16.6	1590
20.2	94.5	1510	18.0	1720
23.9	98.2	1570	18.9	1810
27.1	94.1	1510	18.7	1800

* The estimated value of osmotic suction is based upon the weight of potassium chloride added to the pore fluid and the water content of the compacted specimen.

APPENDIX III

SUCTION TESTS

APPENDIX III. SUCTION TESTS

Total suction data obtained for selected specimens of Vicksburg buckshot clay are listed below:

Water Content	Void Ratio	Total Suction	
%		tsf	kPa
12.2	0.843	57.1	5470
12.5	1.091	61.1	5860
12.7	0.852	60.5	5800
15.9	0.743	8.9	850
16.0	0.744	12.2	1170
16.6	0.965	5.7	550
16.7	0.967	13.8	1330
19.1	0.608	5.0	480
19.7	0.615	5.1	490
20.1	0.622	5.2	500
20.2	0.797	6.0	580
20.7	0.804	3.7	350
23.1	0.706	1.4	140
23.3	0.688	1.0	100
23.5	0.691	1.3	130
23.6	0.713	1.5	140
23.8	0.694	1.7	160
23.9	0.717	1.5	150
26.7	0.789	1.0	100
27.3	0.867	0.7	60
27.4	0.805	0.4	40
27.5	0.806	0.5	50
27.8	0.873	0.7	60
31.3	0.989	0.5	50

Results of preliminary tests used to assess total suction in buckshot clay follow:

Water Content %	Total Suction tsf	Total Suction kPa	Water Content %	Total Suction tsf	Total Suction kPa
12.5	58.9	5640	20.3	1.5	140
15.7	17.1	1630	23.2	2.0	190
18.7	7.0	670	23.9	1.3	130
18.9	7.4	710	25.6	0.9	90
19.3	6.7	640	25.9	1.0	90
19.4	6.1	580	26.0	0.7	70
19.4	8.6	830	26.3	1.3	120
19.5	5.8	550	26.7	0.8	80
19.6	11.0	1060	26.7	0.7	70
19.7	6.3	610	26.8	1.0	90
19.8	4.7	450	26.8	0.5	40
19.8	6.7	650	26.8	0.4	40
19.8	6.2	600	26.8	0.9	90
19.8	2.6	250	26.8	1.5	150
19.9	3.4	320	26.9	0.6	60
19.9	4.4	420	26.9	0.9	80
20.1	3.5	330	26.9	0.3	30
20.2	5.0	470	27.0	0.6	50
20.2	9.2	880	27.0	1.7	160
20.2	2.5	240	27.1	2.8	270
20.3	2.5	230	27.9	1.7	160
20.3	3.3	310	27.9	1.0	100
20.3	4.3	410	32.2	0.9	80

APPENDIX IV

ONE DIMENSIONAL CONSOLIDATION TESTS

APPENDIX IV. ONE DIMENSIONAL CONSOLIDATION TESTS

Seven series of one dimensional consolidation tests were conducted on compacted specimens of Vicksburg buckshot clay; two of the series of tests were conducted on specimens which had been treated with potassium chloride prior to compaction. For each test series, one specimen was tested at the natural water content and the other two specimens were inundated and subjected to initial boundary conditions imposed by the free swell or no swell (constant volume) test prior to consolidating the specimens. The test results are tabulated as applied stress versus void ratio; for each test the void ratios have been corrected for the compressibility of the consolidometer. In addition to the consolidation data for the compacted specimens, the correction factor for device compressibility and consolidation data for slurry specimens of Vicksburg buckshot clay which were used to develop the equivalent consolidation relationship are also presented.

Each specimen was identified using the nomenclature described below. For example, the identification code for specimen number 1D-18-FS-28.9 was:

1D - One dimensional consolidation test

18 - Estimated value of solute suction, tsf, based upon the weight of KCl added to the pore water

FS - Boundary conditions imposed upon the test specimen

- FS - free swell
- NS - no swell (constant volume)
- DR - specimen tested at its natural water content (unsaturated)

28.9 - Initial water content of the test specimen, percent

Date Tests Were Begun: 4 January 1983

Applied Stress tsf*	Test Number			
			1D-00-DR-22.1	
	1D-00-FS-21.0 Void Ratio	1D-00-NS-21.0 Void Ratio	Void Ratio	Suction tsf
Initial	0.804	0.785	0.798	----
0.125	0.797	0.779	0.790	37.5
Inundated	0.865	-----	-----	----
0.25	0.864	-----	0.785	44.3
0.25	-----	-----	0.775	12.2
0.5	0.856	-----	0.775	9.8
0.99	-----	0.784	-----	----
1.0	0.824	-----	0.774	8.2
2	0.751	0.741	0.769	7.3
4	0.684	0.668	0.750	6.2
2	0.690	0.673	-----	----
0.5	0.715	0.697	-----	----
2	0.700	0.6[illegible]	-----	----
4	0.678	0.664	-----	----
8	0.603	0.589	0.691	4.7
16	0.535	0.509	0.555	3.6
8	0.540	0.514	-----	----
2	0.572	0.549	-----	----
8	0.550	0.526	-----	----
16	0.527	0.501	-----	----
32	0.466	0.435	0.476	2.8
64	0.402	0.362	0.393	----
128	0.355	0.291	0.322	----
64	0.365	0.298	0.328	3.3
16	-----	-----	0.371	2.9
8	0.412	0.357	-----	----
4	-----	-----	0.408	2.7
1	0.465	0.422	0.418	2.9
1	0.489	0.455	0.419	2.6
0.25	-----	-----	0.419	3.3
0.125	0.525	0.490	-----	----
0.125	0.554	0.544	-----	----

* 1 tsf = 96 kPa

Date Tests Were Begun: 16 February 1983

Applied Stress tsf*	Test Number			
			1D-00-DR-19.0	
	1D-00-FS-20.0 Void Ratio	1D-00-NS-20.2 Void Ratio	Void Ratio	Suction tsf
Initial	0.945	0.908	0.906	----
0.125	0.946	0.900	0.903	55.3
Inundated	0.966	-----	-----	----
0.25	0.972	-----	0.901	37.4
0.5	0.957	-----	0.900	----
0.545	-----	0.902	-----	----
1.0	0.887	0.855	0.897	32.1
2	0.786	0.785	0.884	21.9
4	0.704	0.755	0.840	18.3
2	0.710	0.756	0.843	14.8
0.5	0.731	0.770	0.849	13.1
2	0.716	0.754	0.846	12.0
4	0.695	0.738	0.839	10.2
8	0.621	0.716	0.716	8.5
16	0.547	0.686	0.565	7.3
8	0.554	0.690	0.568	6.7
2	0.585	0.711	0.575	5.6
8	0.564	0.692	0.571	4.3
16	0.541	0.676	0.563	2.5
32	0.478	0.649	0.491	0.9
64	0.411**	0.598**	0.426	0.3
128	0.353	0.416	0.362	0.1
64	0.360	0.436	0.370	0.1
8	0.419	0.505	0.409	0.2
1	0.486	0.526	0.445	0.2
1	0.511	0.527	0.456	----
0.125	0.549	0.531	0.465	0.2
0.125	0.592	0.538	0.470	0.4

* 1 tsf = 96 kPa
** Soil was extruded

Date Tests Were Begun: 31 March 1983

Applied Stress tsf*	Test Number			
	1D-00-FS-25.9	1D-00-NS-26.0	1D-00-DR-25.4	
	Void Ratio	Void Ratio	Void Ratio	Suction tsf
Initial	0.761	0.769	0.754	----
0.125	0.748	0.757	0.750	3.8
Inundated	0.766	-----	-----	----
0.25	0.766	-----	0.748	1.7
0.44	-----	0.759	-----	----
0.5	0.762	0.758	0.745	1.0
1.0	0.755	0.752	0.740	0.6
2	0.731	0.729	0.726	0.6
4	0.689	0.688	0.694	0.2
2	0.695	0.693	0.698	0.4
0.5	0.717	0.715	0.701	0.1
2	0.705	0.702	0.699	0.2
4	0.685	0.684	0.691	0.2
8	0.624	0.626	0.639	0.1
16	0.545	0.554	0.571	0.1
32	0.466**	0.475	0.497	----
64	0.414	0.401**	0.416**	----
32	0.421	0.408	0.418	----
4	0.465	0.468	0.467	----
0.5	0.521	0.519	0.503	0.1
0.5	0.547	0.548	0.539	0.1

* 1 tsf = 96 kPa

** Soil was extruded

Date Tests Were Begun: 28 April 1983

Applied Stress tsf*	Test Number 1D-00-FS-17.4 Void Ratio	1D-00-NS-16.4 Void Ratio	1D-00-DR-15.9 Void Ratio	1D-00-DR-15.9 Suction tsf
Initial	1.105	1.101	0.997	----
0.125	1.087	1.086	0.996	----
Inundated	1.118	1.084	-----	----
0.25	1.090	1.040	0.995	----
0.5	1.014	0.961	0.993	----
1.0	0.899	0.851	0.988	----
2	0.785	0.751	0.968	----
4	0.687	0.697	0.916	----
2	0.694	0.700	0.919	----
0.5	0.724	0.718	0.925	----
2	0.706	0.705	0.921	12.1
4	0.681	0.697	0.911	12.3
8	0.602	0.676	0.777	12.4
16	0.558	0.643	0.609	10.6
8	0.565	-----	0.611	11.9
2	0.589	-----	0.618	14.4
8	0.566	-----	0.615	11.6
16	0.521	-----	0.603	10.5
32	0.446**	-----	0.483	8.0
64	0.372	-----	0.421	1.6
128	0.301	-----	0.368	1.3
64	0.309	-----	0.372	0.5
8	0.371	-----	0.405	1.0
1	0.440	-----	0.416	2.1
1	0.456	-----	0.420	3.9
0.125	0.503	-----	0.425	5.4
0.125	0.549	-----	0.433	7.8

* 1 tsf = 96 kPa
** Soil was extruded

Date Tests Were Begun: 23 July 1983

Applied Stress tsf*	Test Number			
			1D-18-DR-28.0	
	1D-18-FS-28.9 Void Ratio	1D-18-NS-28.7 Void Ratio	Void Ratio	Suction tsf*
Initial	0.847	0.842	0.855	----
0.125	0.838	0.833	0.851	25.7
Inundated	0.842	-----	-----	----
0.23	-----	0.833	-----	----
0.25	0.837	-----	0.847	25.3
0.5	0.831	0.829	0.836	25.0
1.0	0.810	0.813	0.818	25.3
2	0.761	0.768	0.769	22.0
4	0.700	0.706	0.711	7.0
2	0.704	0.712	0.716	5.2
0.5	0.725	0.731	0.732	5.4
2	0.712	0.720	0.722	5.9
4	0.696	0.703	0.707	5.7
8	0.626	0.635	0.644	10.3
16	0.550	0.555	0.568	11.9
32	-----	-----	0.492	14.4
8	0.554	0.562	0.511	14.3
1	0.603	0.612	0.564	14.0
0.125	0.631	0.655	0.587	14.1
0.125	0.654	0.667	0.623	8.9

* 1 tsf = 96 kPa

Date Tests Were Begun: 13 August 1983

Applied Stress tsf*	Test Number 1D-00-FS-20.9 Void Ratio	1D-00-NS-20.4 Void Ratio	1D-00-DR-20.5 Void Ratio	1D-00-DR-20.5 Suction tsf
Initial	0.626	0.634	0.620	----
0.125	0.638	0.645	0.612	10.0
Inundated	0.662	-----	-----	----
0.25	0.662	-----	0.610	10.6
0.5	0.660	-----	0.608	11.7
0.681	-----	0.647	-----	----
1.0	0.656	0.646	0.607	11.3
2	0.640	0.636	0.600	10.3
4	0.619	0.617	0.591	8.8
8	0.584	0.579	0.573	6.4
16	0.530	0.523	0.532	4.3
32	0.455**	0.459	0.477	4.3
64	0.368	0.385**	0.408	3.3
128	-----	-----	0.330	3.1
64	-----	-----	0.337	0.9
32	-----	0.393	-----	----
8	0.410	0.428	0.375	0.9
1	0.463	0.484	0.418	2.6
1	0.479	0.503	0.435	2.5
0.125	0.516	0.534	0.448	2.6
0.125	0.556	0.574	0.457	4.4

* 1 tsf = 96 kPa
** Soil was extruded

Date Tests Were Begun: 5 September 1983

Applied Stress tsf*	Test Number 1D-18-FS-20.8 Void Ratio	1D-18-NS-20.7 Void Ratio	1D-18-DR-20.0 Void Ratio	1D-18-DR-20.0 Suction tsf*
Initial	0.801	0.812	0.851	----
0.125	0.806	0.819	0.847	10.3
Inundated	0.836	-----	-----	----
0.25	0.838	-----	0.844	11.1
0.5	0.835	-----	0.841	10.6
0.636	-----	0.822	-----	----
1.0	0.818	0.817	0.837	10.7
2	0.768	0.769	0.824	10.2
4	0.694	0.690	0.781	10.0
2	0.699	0.695	0.783	10.2
0.5	0.722	0.718	0.788	10.0
2	0.708	0.704	0.786	9.7
4	0.690	0.687	0.781	9.8
8	0.610	0.610	0.660	5.1
16	0.531	0.532	0.546	2.3
8	0.538	0.539	0.551	2.6
2	0.568	0.576	0.561	2.8
8	0.547	0.549	0.556	2.8
16	0.523	0.526	0.543	2.9
32	0.458**	0.476**	0.478	4.1
64	0.398	0.432	0.412	11.0
128	-----	-----	0.349	12.6
64	-----	-----	0.355	13.1
8	0.439	0.465	0.404	12.0
1	0.499	0.519	0.455	11.8
1	0.509	0.526	0.473	10.2
0.125	0.555	0.566	0.505	11.1
0.125	0.591	0.603	0.517	10.7

* 1 tsf = 96 kPa

** Soil was extruded

CONSOLIDATION OF VICKSBURG BUCKSHOT CLAY FROM A SLURRY

Applied Stress tsf	Applied Stress kPa	Void Ratio	Reference
0.14	13	1.287	After Donaghe and Townsend, 1975
0.33	32	1.210	
0.50	48	1.150	
1.14	109	1.010	
1.55	149	0.962	
2.88	276	0.849	
3.07	294	0.828	
0.14	13	1.802	After Peters, Leavell and Johnson, 1982
0.18	17	1.695	
0.29	28	1.376	
0.58	56	1.212	
1.02	98	1.096	
1.53	147	1.015	
2.05	196	0.954	
3.15	302	0.865	

DEVICE COMPRESSIBILITY CHECK
Date: 10 October 1983

Applied* Stress tsf	Average Compressibility inch**
0.125	0.0000
0.25	0.0004
0.5	0.0012
1.0	0.0033
2	0.0040
4	0.0055
2	0.0051
0.5	0.0035
2	0.0049
4	0.0056
8	0.0073
16	0.0091
8	0.0083
2	0.0066
8	0.0080
16	0.0091
32	0.0110
64	0.0135
128	0.0175
64	0.0156
8	0.0113
1	0.0083
0.125	0.0065

* 1 tsf = 96 kPa
** 1 inch = 25.4 mm

APPENDIX V

TRIAXIAL COMPRESSION TESTS ON SATURATED SPECIMENS

APPENDIX V. TRIAXIAL COMPRESSION TESTS ON SATURATED SPECIMENS

Twenty back pressure saturated triaxial tests with pore pressure measurements were conducted on specimens of Vicksburg buckshot clay which had been compacted at water contents wet and dry of optimum. Specimens were allowed to free swell upon inundation. The axial and radial strains which occurred during swell were assumed to be isotropic and based upon the axial strain measurements. None of the back pressure saturated specimens were treated with potassium chloride prior to compaction.

Each specimen was identified using the nomenclature described below. For example, the identification code for specimen number TXS-0-FS-27-160-4(2) was:

TXS - Triaxial shear test

0 - Estimated value of solute suction, tsf, based upon the weight of KCl added to the pore water

FS - Free swell boundary conditions imposed upon the test specimen

27 - Nominal water content of the test specimen, percent

160 - Effective isotropic confining pressure used to consolidate the test specimen, psi (1 psi = 0.07 tsf = 6.9 kPa)

4 - Numerical value analogous to an overconsolidation ratio. For a value of 1, the specimen was sheared at the consolidation stress; for a value of 2, the specimen was rebounded to 1/2 of the consolidation stress prior to shear; for a value of 4, the specimen was rebounded to 1/4 of the consolidation stress prior to shear; etc.

(2) - Number of the test specimen which was subjected to that particular consolidation and rebound sequence prior to shear. (1) - first specimen, (2) - second specimen, etc.

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-20-40-1

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	3.000 IN	W/C:	20.1 %	DRY DENSITY:	92.6 PCF
DIAMETER:	1.395 IN	GS:	2.72	VOID RATIO:	0.833

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.876 AT A STRESS OF 0.34 TSF

CONSOLIDATED TO A VOID RATIO OF 0.681 BY AN EFFECTIVE STRESS OF 2.88 TSF

REBOUNDED TO A VOID RATIO OF 0.681 BY AN EFFECTIVE STRESS OF 2.88 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 6.989 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.946 IN	W/C:	25.0 %	CHAMBER PRESSURE:	4.82 TSF
DIAMETER:	1.301 IN	B-VALUE:	1.00	PORE PRESSURE:	1.94 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	2.880	2.880	1.000	0.000	2.880	0.000	0.412	0.412	-1.079
8	0.297	0.136	0.	0.	3.177	2.880	1.103	0.149	3.029	0.021	0.455	0.412	-0.986
9	0.297	0.204	0.	0.	3.177	2.880	1.103	0.148	3.028	0.021	0.455	0.412	-0.986
10	0.377	0.238	0.014	0.038	3.243	2.866	1.132	0.189	3.054	0.027	0.464	0.410	-0.958
11	0.593	0.238	0.086	0.146	3.387	2.794	1.212	0.297	3.090	0.042	0.485	0.400	-0.876
12	1.185	0.272	0.367	0.310	3.698	2.513	1.472	0.593	3.105	0.085	0.529	0.360	-0.638
13	1.551	0.611	0.655	0.422	3.776	2.225	1.697	0.776	3.001	0.111	0.540	0.318	-0.469
14	2.028	1.969	1.109	0.547	3.799	1.771	2.145	1.014	2.785	0.145	0.544	0.253	-0.235
15	2.130	2.580	1.253	0.588	3.757	1.627	2.309	1.065	2.692	0.152	0.538	0.233	-0.177
16	2.223	3.327	1.354	0.609	3.749	1.526	2.456	1.111	2.638	0.159	0.536	0.218	-0.129
17	2.322	4.379	1.397	0.602	3.805	1.483	2.566	1.161	2.644	0.166	0.544	0.212	-0.089
18	2.381	5.160	1.469	0.617	3.792	1.411	2.687	1.190	2.602	0.170	0.543	0.202	-0.058
19	2.469	6.687	1.498	0.607	3.852	1.382	2.786	1.235	2.617	0.177	0.551	0.198	-0.024
20	2.573	10.183	1.483	0.576	3.970	1.397	2.842	1.287	2.683	0.184	0.568	0.200	0.006
21	2.612	13.578	1.447	0.554	4.045	1.433	2.823	1.306	2.739	0.187	0.579	0.205	0.011
22	2.666	16.972	1.397	0.524	4.150	1.483	2.798	1.333	2.816	0.191	0.594	0.212	0.019
23	2.644	20.061	1.296	0.490	4.228	1.584	2.669	1.322	2.906	0.189	0.605	0.227	-0.007
24	2.631	21.419	1.325	0.503	4.187	1.555	2.692	1.316	2.871	0.188	0.599	0.223	-0.005

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-20-40-2

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT: 2.995 IN W/C: 20.8 % DRY DENSITY: 94.7 PCF

DIAMETER: 1.416 IN GS: 2.72 VOID RATIO: 0.793

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.831 AT A STRESS OF 0.35 TSF

CONSOLIDATED TO A VOID RATIO OF 0.666 BY AN EFFECTIVE STRESS OF 2.76 TSF

REBOUNDED TO A VOID RATIO OF 0.688 BY AN EFFECTIVE STRESS OF 1.34 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 6.675 TSF

PRE-SHEAR CONDITIONS:

HEIGHT: 2.942 IN W/C: 26.1 % CHAMBER PRESSURE: 7.90 TSF

DIAMETER: 1.356 IN B-VALUE: 0.95 PORE PRESSURE: 6.56 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	1.339	1.339	1.000	0.000	1.339	0.000	0.201	0.201	-0.770
8	0.075	0.	-0.014	-0.193	1.428	1.354	1.055	0.037	1.391	0.006	0.214	0.203	-0.749
9	0.075	0.068	-0.022	-0.289	1.435	1.361	1.055	0.037	1.398	0.006	0.215	0.204	-0.750
10	0.099	0.102	-0.043	-0.434	1.482	1.382	1.072	0.050	1.432	0.007	0.222	0.207	-0.746
11	0.099	0.136	0.	0.	1.439	1.339	1.074	0.050	1.389	0.007	0.216	0.201	-0.738
12	0.149	0.204	-0.007	-0.048	1.495	1.346	1.111	0.074	1.421	0.011	0.224	0.202	-0.724
13	0.223	0.272	0.007	0.032	1.555	1.332	1.167	0.112	1.443	0.017	0.233	0.200	-0.698
14	0.938	0.476	0.180	0.192	2.097	1.159	1.809	0.469	1.628	0.070	0.314	0.174	-0.441
15	1.206	0.612	0.238	0.197	2.307	1.102	2.095	0.603	1.704	0.090	0.346	0.165	-0.346
16	1.649	1.326	0.259	0.157	2.729	1.080	2.527	0.824	1.904	0.124	0.409	0.162	-0.202
17	1.808	2.243	0.302	0.167	2.845	1.037	2.744	0.904	1.941	0.135	0.426	0.155	-0.144
18	1.956	3.841	0.346	0.177	2.950	0.994	2.969	0.978	1.972	0.147	0.442	0.149	-0.090
19	2.040	5.099	0.389	0.191	2.990	0.950	3.146	1.020	1.970	0.153	0.448	0.142	-0.055
20	2.101	6.730	0.367	0.175	3.073	0.972	3.162	1.051	2.023	0.157	0.460	0.146	-0.040
21	2.177	10.129	0.288	0.132	3.228	1.051	3.071	1.088	2.140	0.163	0.484	0.157	-0.031
22	2.248	13.528	0.252	0.112	3.335	1.087	3.068	1.124	2.211	0.168	0.500	0.163	-0.015
23	2.278	16.927	0.194	0.085	3.423	1.145	2.990	1.139	2.284	0.171	0.513	0.172	-0.016
24	2.216	20.496	0.166	0.075	3.390	1.174	2.889	1.108	2.282	0.166	0.508	0.176	-0.041
25	2.208	21.618	0.151	0.068	3.396	1.188	2.858	1.104	2.292	0.165	0.509	0.178	-0.046

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-20-40-4

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT: 3.001 IN W/C: 20.5 % DRY DENSITY: 93.2 PCF

DIAMETER: 1.415 IN GS: 2.72 VOID RATIO: 0.822

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.861 AT A STRESS OF 0.37 TSF

CONSOLIDATED TO A VOID RATIO OF 0.694 BY AN EFFECTIVE STRESS OF 2.89 TSF

REBOUNDED TO A VOID RATIO OF 0.744 BY AN EFFECTIVE STRESS OF 0.73 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 4.694 TSF

PRE-SHEAR CONDITIONS:

HEIGHT: 2.970 IN W/C: 26.7 % CHAMBER PRESSURE: 2.23 TSF

DIAMETER: 1.368 IN B-VALUE: 0.96 PORE PRESSURE: 1.50 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	0.727	0.727	1.000	0.000	0.727	0.000	0.155	0.155	-0.502
8	0.073	0.	-0.036	-0.490	0.837	0.763	1.096	0.037	0.800	0.008	0.178	0.163	-0.485
9	0.171	0.	-0.014	-0.084	0.913	0.742	1.231	0.086	0.827	0.018	0.194	0.158	-0.450
10	0.294	0.	0.072	0.245	0.949	0.655	1.449	0.147	0.802	0.031	0.202	0.140	-0.396
11	0.440	0.067	0.072	0.164	1.095	0.655	1.672	0.220	0.875	0.047	0.233	0.140	-0.350
12	0.464	0.101	0.050	0.109	1.141	0.677	1.686	0.232	0.909	0.049	0.243	0.144	-0.346
13	0.562	0.135	0.122	0.218	1.167	0.605	1.[illegible]9	0.281	0.886	0.060	0.248	0.129	-0.302
14	0.659	0.202	0.144	0.219	1.242	0.583	2.129	0.329	0.912	0.070	0.265	0.124	-0.268
15	0.706	0.269	0.115	0.163	1.318	0.612	2.154	0.353	0.965	0.075	0.281	0.130	-0.258
16	0.849	0.471	0.086	0.102	1.490	0.641	2.325	0.424	1.065	0.090	0.317	0.137	-0.218
17	0.895	0.606	0.130	0.145	1.493	0.598	2.498	0.447	1.045	0.095	0.318	0.127	-0.196
18	1.240	1.313	0.130	0.105	1.837	0.598	3.075	0.620	1.217	0.132	0.391	0.127	-0.087
19	1.404	2.222	0.115	0.082	2.016	0.612	3.294	0.702	1.314	0.150	0.429	0.130	-0.038
20	1.540	3.805	0.094	0.061	2.174	0.634	3.430	0.770	1.404	0.164	0.463	0.135	0.001
21	1.589	5.051	0.101	0.063	2.215	0.626	3.537	0.794	1.421	0.169	0.472	0.133	0.018
22	1.664	6.667	0.094	0.056	2.298	0.634	3.627	0.832	1.466	0.177	0.489	0.135	0.040
23	1.729	10.034	-0.007	-0.004	2.463	0.734	3.354	0.865	1.599	0.184	0.525	0.156	0.042
24	1.775	13.401	-0.050	-0.028	2.553	0.778	3.283	0.888	1.665	0.189	0.544	0.166	0.048
25	1.787	16.768	-0.101	-0.056	2.615	0.828	3.159	0.894	1.722	0.190	0.557	0.176	0.043
26	1.780	20.303	-0.144	-0.081	2.651	0.871	3.043	0.890	1.761	0.190	0.565	0.186	0.032
27	1.767	21.414	-0.166	-0.094	2.660	0.893	2.979	0.884	1.776	0.188	0.567	0.190	0.024

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-20-40-8

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	2.993 IN	W/C:	20.5 %	DRY DENSITY:	92.9 PCF
DIAMETER:	1.411 IN	GS:	2.72	VOID RATIO:	0.827

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.863 AT A STRESS OF 0.26 TSF

CONSOLIDATED TO A VOID RATIO OF 0.683 BY AN EFFECTIVE STRESS OF 2.89 TSF

REBOUNDED TO A VOID RATIO OF 0.751 BY AN EFFECTIVE STRESS OF 0.38 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 4.501 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.970 IN	W/C:	27.8 %	CHAMBER PRESSURE:	1.89 TSF
DIAMETER:	1.362 IN	B-VALUE:	1.00	PORE PRESSURE:	1.51 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	0.374	0.374	1.000	0.000	0.374	0.000	0.083	0.083	-0.421
8	0.074	0.	-0.014	-0.194	0.463	0.389	1.191	0.037	0.426	0.008	0.103	0.086	-0.401
9	0.124	0.	0.014	0.117	0.484	0.360	1.343	0.062	0.422	0.014	0.107	0.080	-0.380
10	0.247	0.	0.050	0.204	0.571	0.324	1.762	0.124	0.448	0.027	0.127	0.072	-0.334
11	0.271	0.067	0.050	0.186	0.595	0.324	1.837	0.136	0.460	0.030	0.132	0.072	-0.326
12	0.320	0.101	0.058	0.180	0.637	0.317	2.012	0.160	0.477	0.036	0.142	0.070	-0.310
13	0.419	0.135	0.101	0.241	0.692	0.274	2.531	0.209	0.483	0.047	0.154	0.061	-0.271
14	0.492	0.202	0.101	0.205	0.766	0.274	2.798	0.246	0.520	0.055	0.170	0.061	-0.248
15	0.565	0.269	0.065	0.115	0.875	0.310	2.825	0.283	0.592	0.063	0.194	0.069	-0.231
16	0.636	0.471	0.115	0.181	0.895	0.259	3.454	0.318	0.577	0.071	0.199	0.058	-0.200
17	0.781	0.606	0.130	0.166	1.025	0.245	4.189	0.390	0.635	0.087	0.228	0.054	-0.151
18	0.986	1 313	0.101	0.102	1.259	0.274	4.603	0.493	0.767	0.110	0.280	0.061	-0.092
19	1.109	2.222	0.058	0.052	1.426	0.317	4.501	0.555	0.871	0.123	0.317	0.070	-0.061
20	1.188	3 805	0.014	0.012	1.548	0.360	4.299	0.594	0.954	0.132	0.344	0.080	-0.044
21	1.224	5.051	0.	0.	1.598	0.374	4.269	0.612	0.986	0.136	0.355	0.083	-0.036
22	1.291	6.667	-0.036	-0.028	1.701	0.410	4.146	0.645	1.056	0.143	0.378	0.091	-0.021
23	1.363	10.034	-0.108	-0.079	1.845	0.482	3.825	0.681	1.164	0.151	0.410	0.107	-0.012
24	1.399	13.401	-0.144	-0.103	1.917	0.518	3.698	0.699	1.218	0.155	0.426	0.115	-0.007
25	1.404	16.768	-0.187	-0.133	1.965	0.562	3.499	0.702	1.263	0.156	0.437	0.125	-0.014
26	1.394	20.303	-0.223	-0.160	1 992	0 598	3 333	0.697	1.295	0.155	0.442	0.133	-0 023
27	1.406	21.414	-0.245	-0.174	2.026	0.619	3.271	0.703	1.322	0.156	0.450	0.138	-0.023

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-20-160-1

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT: 3.000 IN W/C: 20.3 % DRY DENSITY: 95.1 PCF
DIAMETER: 1.400 IN GS: 2.72 VOID RATIO: 0.785

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.840 AT A STRESS OF 0.27 TSF
CONSOLIDATED TO A VOID RATIO OF 0.520 BY AN EFFECTIVE STRESS OF 11.48 TSF
REBOUNDED TO A VOID RATIO OF 0.520 BY AN EFFECTIVE STRESS OF 11.48 TSF
EQUIVALENT CONSOLIDATION STRESS, P_e, OF 23.510 TSF

PRE-SHEAR CONDITIONS:

HEIGHT: 2.863 IN W/C: 20.5 % CHAMBER PRESSURE: 13.42 TSF
DIAMETER: 1.243 IN B-VALUE: 1.00 PORE PRESSURE: 1.94 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	11.484	11.484	1.000	0.000	11.484	0.000	0.488	0.488	-3.963
8	0.325	0.140	0.007	0.022	11.802	11.477	1.028	0.163	11.639	0.007	0.502	0.488	-3.859
9	0.502	0.210	0.014	0.029	11.971	11.470	1.044	0.251	11.720	0.011	0.509	0.488	-3.802
10	0.501	0.244	0.043	0.086	11.942	11.441	1.044	0.251	11.691	0.011	0.508	0.487	-3.797
11	0.560	0.244	0.101	0.180	11.943	11.383	1.049	0.280	11.663	0.012	0.508	0.484	-3.768
12	1.680	0.279	0.461	0.274	12.703	11.023	1.152	0.840	11.863	0.036	0.540	0.469	-3.349
13	3.714	0.629	1.310	0.353	13.888	10.174	1.365	1.857	12.031	0.079	0.591	0.433	-2.551
14	5.958	2.026	3.118	0.523	14.324	8.366	1.712	2.979	11.345	0.127	0.609	0.356	-1.510
15	6.492	2.655	3.650	0.562	14.326	7.834	1.829	3.246	11.080	0.138	0.609	0.333	-1.243
16	6.907	3.423	4.054	0.587	14.337	7.430	1.930	3.453	10.884	0.147	0.610	0.316	-1.037
17	7.363	4.506	4.414	0.599	14.433	7.070	2.041	3.681	10.752	0.157	0.614	0.301	-0.827
18	7.604	5.309	4.622	0.608	14.465	6.862	2.108	3.802	10.663	0.162	0.615	0.292	-0.713
19	7.931	6.881	4.824	0.608	14.591	6.660	2.191	3.965	10.625	0.169	0.621	0.283	-0.572
20	8.215	10.479	4.925	0.599	14.774	6.559	2.253	4.108	10.667	0.175	0.628	0.279	-0.464
21	8.181	13.971	4.882	0.597	14.783	6.602	2.239	4.090	10.693	0.174	0.629	0.281	-0.483
22	8.075	17.464	4.810	0.596	14.749	6.674	2.210	4.037	10.712	0.172	0.627	0.284	-0.530
23	7.891	20.643	4.745	0.601	14.630	6.739	2.171	3.946	10.685	0.168	0.622	0.287	-0.599
24	7.799	22.040	4.759	0.610	14.523	6.725	2.160	3.899	10.624	0.166	0.618	0.286	-0.626

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-20-160-2

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	3.000 IN	W/C:	19.8 %	DRY DENSITY:	94.1 PCF
DIAMETER:	1.392 IN	GS:	2.72	VOID RATIO:	0.805

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.861 AT A STRESS OF 0.32 TSF

CONSOLIDATED TO A VOID RATIO OF 0.549 BY AN EFFECTIVE STRESS OF 12.36 TSF

REBOUNDED TO A VOID RATIO OF 0.566 BY AN EFFECTIVE STRESS OF 5.78 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 16.058 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.889 IN	W/C:	21.2 %	CHAMBER PRESSURE:	7.67 TSF
DIAMETER:	1.249 IN	B-VALUE:	0.99	PORE PRESSURE:	1.89 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	5.782	5.782	1.000	0.000	5.782	0.000	0.360	0.360	-2.325
8	0.322	0.138	0.	0.	6.104	5.782	1.056	0.161	5.943	0.010	0.380	0.360	-2.224
9	0.322	0.208	0.	0.	6.103	5.782	1.056	0.161	5.942	0.010	0.380	0.360	-2.224
10	0.321	0.242	0.007	0.022	6.096	5.774	1.056	0.161	5.935	0.010	0.380	0.360	-2.223
11	0.321	0.242	0.014	0.045	6.089	5.767	1.056	0.161	5.928	0.010	0.379	0.359	-2.221
12	0.526	0.277	0.086	0.164	6.221	5.695	1.092	0.263	5.958	0.016	0.387	0.355	-2.144
13	0.816	0.346	0.137	0.168	6.461	5.645	1.145	0.408	6.053	0.025	0.402	0.352	-2.043
14	1.369	0.381	0.245	0.179	6.906	5.537	1.247	0.685	6.221	0.043	0.430	0.345	-1.849
15	1.918	0.485	0.418	0.218	7.282	5.364	1.358	0.959	6.323	0.060	0.454	0.334	-1.644
16	2.409	0.554	0.533	0.221	7.658	5.249	1.459	1.204	6.453	0.075	0.477	0.327	-1.468
17	2.782	0.623	0.655	0.236	7.908	5.126	1.543	1.391	6.517	0.087	0.493	0.319	-1.328
18	3.154	0.692	0.706	0.224	8.230	5.076	1.621	1.577	6.653	0.098	0.513	0.316	-1.201
19	3.860	0.900	0.806	0.209	8.835	4.975	1.776	1.930	6.905	0.120	0.550	0.310	-0.960
20	4.571	1.281	0.792	0.173	9.561	4.990	1.916	2.286	7.275	0.142	0.595	0.311	-0.739
21	5.119	2.008	0.765	0.149	10.137	5.018	2.020	2.559	7.578	0.159	0.631	0.313	-0.572
22	5.550	2.631	0.814	0.147	10.518	4.968	2.117	2.775	7.743	0.173	0.655	0.309	-0.427
23	5.879	3.392	0.864	0.147	10.797	4.918	2.196	2.940	7.857	0.183	0.672	0.306	-0.314
24	6.213	4.465	0.907	0.146	11.087	4.874	2.275	3.106	7.981	0.193	0.690	0.304	-0.201
25	6.394	5.261	0.965	0.151	11.211	4.817	2.327	3.197	8.014	0.199	0.698	0.300	-0.133
26	6.686	6.819	0.994	0.149	11.474	4.788	2.396	3.343	8.131	0.208	0.715	0.298	-0.035
27	6.811	10.384	0.922	0.135	11.671	4.860	2.401	3.406	8.266	0.212	0.727	0.303	-0.009
28	6.823	13.846	0.821	0.120	11.784	4.961	2.375	3.412	8.372	0.212	0.734	0.309	-0.024
29	6.747	17.307	0.727	0.108	11.802	5.054	2.335	3.374	8.428	0.210	0.735	0.315	-0.065
30	6.609	20.457	0.634	0.096	11.757	5.148	2.284	3.304	8.452	0.206	0.732	0.321	-0.126
31	6.525	21.841	0.641	0.098	11.665	5.141	2.269	3.262	8.403	0.203	0.726	0.320	-0.151

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-20-160-4

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	2.996 IN	W/C:	19.3 %	DRY DENSITY:	93.3 PCF
DIAMETER:	1.395 IN	GS:	2.72	VOID RATIO:	0.820

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.876 AT A STRESS OF 0.23 TSF
CONSOLIDATED TO A VOID RATIO OF 0.525 BY AN EFFECTIVE STRESS OF 11.48 TSF
REBOUNDED TO A VOID RATIO OF 0.576 BY AN EFFECTIVE STRESS OF 2.92 TSF
EQUIVALENT CONSOLIDATION STRESS, P_e, OF 14.841 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.884 IN	W/C:	22.2 %	CHAMBER PRESSURE:	8.76 TSF
DIAMETER:	1.250 IN	B-VALUE:	0.95	PORE PRESSURE:	5.84 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	2.916	2.916	1.000	0.000	2.916	0.000	0.196	0.196	-1.700
8	0.323	0.035	0.086	0.268	3.152	2.830	1.114	0.161	2.991	0.011	0.212	0.191	-1.582
9	0.440	0.035	0.115	0.262	3.241	2.801	1.157	0.220	3.021	0.015	0.218	0.189	-1.540
10	0.527	0.069	0.108	0.205	3.335	2.808	1.188	0.264	3.072	0.018	0.225	0.189	-1.514
11	0.850	0.069	0.144	0.169	3.622	2.772	1.307	0.425	3.197	0.029	0.244	0.187	-1.406
12	1.200	0.104	0.317	0.264	3.800	2.599	1.462	0.600	3.199	0.040	0.256	0.175	-1.263
13	2.383	0.451	0.504	0.212	4.795	2.412	1.988	1.191	3.603	0.080	0.323	0.163	-0.856
14	3.074	0.971	0.482	0.157	5.508	2.434	2.263	1.537	3.971	0.104	0.371	0.164	-0.642
15	3.448	1.352	0.439	0.127	5.925	2.477	2.392	1.724	4.201	0.116	0.399	0.167	-0.533
16	3.838	1.803	0.382	0.099	6.372	2.534	2.514	1.919	4.453	0.129	0.429	0.171	-0.421
17	4.052	2.254	0.281	0.069	6.687	2.635	2.538	2.026	4.661	0.137	0.451	0.178	-0.372
18	4.325	2.913	0.259	0.060	6.982	2.657	2.628	2.163	4.819	0.146	0.470	0.179	-0.290
19	4.484	3.537	0.216	0.048	7.184	2.700	2.661	2.242	4.942	0.151	0.484	0.182	-0.248
20	4.713	4.473	0.115	0.024	7.514	2.801	2.683	2.357	5.157	0.159	0.506	0.189	-0.194
21	4.856	5.374	0.058	0.012	7.715	2.858	2.699	2.428	5.286	0.164	0.520	0.193	-0.160
22	5.045	6.484	0.050	0.010	7.911	2.866	2.761	2.523	5.388	0.170	0.533	0.193	-0.101
23	5.149	7.802	-0.050	-0.010	8.115	2.966	2.736	2.574	5.541	0.173	0.547	0.200	-0.088
24	5.328	10.402	-0.130	-0.024	8.373	3.046	2.749	2.664	5.709	0.179	0.564	0.205	-0.046
25	5.426	13.870	-0.295	-0.054	8.638	3.211	2.690	2.713	5.924	0.183	0.582	0.216	-0.045
26	5.434	17.337	-0.360	-0.066	8.710	3.276	2.659	2.717	5.993	0.183	0.587	0.221	-0.055
27	5.310	20.804	-0.374	-0.071	8.601	3.290	2.614	2.655	5.946	0.179	0.580	0.222	-0.097
28	5.234	23.301	-0.418	-0.080	8.567	3.334	2.570	2.617	5.950	0.176	0.577	0.225	-0.129

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-20-160-8

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	2.996 IN	W/C:	22.2 %	DRY DENSITY:	94.1 PCF
DIAMETER:	1.391 IN	GS:	2.72	VOID RATIO:	0.804

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.866 AT A STRESS OF 0.38 TSF
CONSOLIDATED TO A VOID RATIO OF 0.526 BY AN EFFECTIVE STRESS OF 11.50 TSF
REBOUNDED TO A VOID RATIO OF 0.607 BY AN EFFECTIVE STRESS OF 1.47 TSF
EQUIVALENT CONSOLIDATION STRESS, P_e, OF 11.724 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.912 IN	W/C:	23.3 %	CHAMBER PRESSURE:	7.30 TSF
DIAMETER:	1.271 IN	B-VALUE:	0.94	PORE PRESSURE:	5.83 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	1.469	1.469	1.000	0.000	1.469	0.000	0.125	0.125	-1.189
8	0.227	0.034	0.065	0.286	1.631	1.404	1.161	0.113	1.517	0.010	0.139	0.120	-1.105
9	0.453	0.034	0.101	0.222	1.821	1.368	1.331	0.227	1.595	0.019	0.155	0.117	-1.027
10	0.566	0.069	0.108	0.191	1.927	1.361	1.416	0.283	1.644	0.024	0.164	0.116	-0.990
11	0.736	0.069	0.137	0.186	2.068	1.332	1.553	0.368	1.700	0.031	0.176	0.114	-0.931
12	0.962	0.103	0.238	0.247	2.193	1.231	1.781	0.481	1.712	0.041	0.187	0.105	-0.842
13	1.601	0.446	0.338	0.211	2.731	1.130	2.416	0.800	1.931	0.068	0.233	0.096	-0.622
14	2.111	0.962	0.353	0.167	3.227	1.116	2.892	1.056	2.172	0.090	0.275	0.095	-0.458
15	2.453	1.339	0.302	0.123	3.619	1.166	3.103	1.226	2.393	0.105	0.309	0.099	-0.360
16	2.730	1.786	0.252	0.092	3.946	1.217	3.243	1.365	2.582	0.116	0.337	0.104	-0.282
17	2.947	2.232	0.166	0.056	4.250	1.303	3.261	1.473	2.777	0.126	0.363	0.111	-0.230
18	3.173	2.885	0.101	0.032	4.541	1.368	3.319	1.586	2.954	0.135	0.387	0.117	-0.171
19	3.341	3.503	0.029	0.009	4.781	1.440	3.320	1.671	3.111	0.142	0.408	0.123	-0.131
20	3.482	4.430	-0.108	-0.031	5.059	1.577	3.208	1.741	3.318	0.148	0.431	0.134	-0.112
21	3.618	5.323	-0.194	-0.054	5.281	1.663	3.175	1.809	3.472	0.154	0.450	0.142	-0.085
22	3.706	6.422	-0.274	-0.074	5.448	1.742	3.127	1.853	3.595	0.158	0.465	0.149	-0.072
23	3.818	7.727	-0.403	-0.106	5.690	1.872	3.040	1.909	3.781	0.163	0.485	0.160	-0.060
24	3.972	10.302	-0.533	-0.134	5.974	2.002	2.985	1.986	3.988	0.169	0.510	0.171	-0.036
25	4.039	13.736	-0.720	-0.178	6.228	2.189	2.845	2.020	4.208	0.172	0.531	0.187	-0.049
26	4.031	17.170	-0.785	-0.195	6.285	2.254	2.789	2.016	4.269	0.172	0.536	0.192	-0.064
27	3.943	20.604	-0.850	-0.215	6.261	2.318	2.701	1.971	4.290	0.168	0.534	0.198	-0.104
28	3.892	23.077	-0.936	-0.240	6.297	2.405	2.619	1.946	4.351	0.166	0.537	0.205	-0.136

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-20-160-16

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	2.992 IN	W/C:	19.6 %	DRY DENSITY:	93.4 PCF
DIAMETER:	1.395 IN	GS:	2.72	VOID RATIO:	0.817

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.873 AT A STRESS OF 0.29 TSF
CONSOLIDATED TO A VOID RATIO OF 0.561 BY AN EFFECTIVE STRESS OF 11.51 TSF
REBOUNDED TO A VOID RATIO OF 0.658 BY AN EFFECTIVE STRESS OF 0.71 TSF
EQUIVALENT CONSOLIDATION STRESS, P_e, OF 8.157 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.917 IN	W/C:	24.3 %	CHAMBER PRESSURE:	6.61 TSF
DIAMETER:	1.304 IN	B-VALUE:	0.96	PORE PRESSURE:	5.90 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	0.713	0.713	1.000	0.000	0.713	0.000	0.087	0.087	-0.770
8	0.162	0.034	0.058	0.356	0.817	0.655	1.247	0.081	0.736	0.010	0.100	0.080	-0.708
9	0.404	0.034	0.086	0.214	1.031	0.626	1.645	0.202	0.829	0.025	0.126	0.077	-0.626
10	0.458	0.069	0.101	0.220	1.070	0.612	1.748	0.229	0.841	0.028	0.131	0.075	-0.607
11	0.592	0.069	0.122	0.207	1.183	0.590	2.004	0.296	0.887	0.036	0.145	0.072	-0.560
12	0.754	0.103	0.180	0.239	1.286	0.533	2.414	0.377	0.910	0.046	0.158	0.065	-0.499
13	1.122	0.446	0.216	0.192	1.619	0.497	3.259	0.561	1.058	0.069	0.198	0.061	-0.376
14	1.454	0.960	0.209	0.144	1.958	0.504	3.885	0.727	1.231	0.089	0.240	0.062	-0.273
15	1.626	1.337	0.180	0.111	2.159	0.533	4.052	0.813	1.346	0.100	0.265	0.065	-0.224
16	1.870	1.783	0.137	0.073	2.446	0.576	4.247	0.935	1.511	0.115	0.300	0.071	-0.155
17	2.007	2.228	0.072	0.036	2.648	0.641	4.133	1.004	1.645	0.123	0.325	0.079	-0.124
18	2.158	2.880	0.014	0.007	2.856	0.698	4.090	1.079	1.777	0.132	0.350	0.086	-0.087
19	2.305	3.497	-0.058	-0.025	3.076	0.770	3.992	1.153	1.923	0.141	0.377	0.094	-0.054
20	2.432	4.422	-0.173	-0.071	3.318	0.886	3.747	1.216	2.102	0.149	0.407	0.109	-0.035
21	2.531	5.314	-0.252	-0.100	3.496	0.965	3.624	1.266	2.230	0.155	0.429	0.118	-0.019
22	2.614	6.411	-0.338	-0.129	3.665	1.051	3.487	1.307	2.358	0.160	0.449	0.129	-0.009
23	2.725	7.713	-0.446	-0.164	3.885	1.159	3.351	1.363	2.522	0.167	0.476	0.142	0.006
24	2.860	10.285	-0.569	-0.199	4.142	1.282	3.232	1.430	2.712	0.175	0.508	0.157	0.026
25	2.975	13.713	-0.720	-0.242	4.408	1.433	3.077	1.488	2.920	0.182	0.540	0.176	0.034
26	2.981	17.141	-0.806	-0.271	4.500	1.519	2.962	1.490	3.010	0.183	0.552	0.186	0.020
27	2.979	20.363	-0.857	-0.288	4.549	1.570	2.898	1.490	3.059	0.183	0.558	0.192	0.010
28	2.883	23.037	-0.929	-0.322	4.525	1.642	2.756	1.442	3.083	0.177	0.555	0.201	-0.033

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-40-1

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	3.015 IN	W/C:	27.0 %	DRY DENSITY:	95.0 PCF
DIAMETER:	1.380 IN	GS:	2.72	VOID RATIO:	0.707

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.767 AT A STRESS OF 0.30 TSF

CONSOLIDATED TO A VOID RATIO OF 0.670 BY AN EFFECTIVE STRESS OF 2.79 TSF

REBOUNDED TO A VOID RATIO OF 0.670 BY AN EFFECTIVE STRESS OF 2.79 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 7.520 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.941 IN	W/C:	26.7 %	CHAMBER PRESSURE:	5.04 TSF
DIAMETER:	1.321 IN	B-VALUE:	1.00	PORE PRESSURE:	2.25 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	2.786	2.786	1.000	0.000	2.786	0.000	0.371	0.371	-1.104
8	0.367	0.102	0.036	0.098	3.117	2.750	1.133	0.183	2.934	0.024	0.415	0.366	-0.981
9	0.550	0.102	0.101	0.183	3.236	2.686	1.205	0.275	2.961	0.037	0.430	0.357	-0.912
10	0.838	0.102	0.194	0.232	3.430	2.592	1.323	0.419	3.011	0.056	0.456	0.345	-0.803
11	0.995	0.136	0.259	0.261	3.522	2.527	1.394	0.497	3.025	0.066	0.468	0.336	-0.742
12	1.124	0.204	0.331	0.295	3.579	2.455	1.458	0.562	3.017	0.075	0.476	0.326	-0.688
13	1.435	0.306	0.504	0.351	3.717	2.282	1.629	0.718	3.000	0.095	0.494	0.304	-0.558
14	1.715	0.510	0.684	0.399	3.817	2.102	1.816	0.857	2.960	0.114	0.508	0.280	-0.437
15	1.959	0.884	0.871	0.445	3.875	1.915	2.023	0.980	2.895	0.130	0.515	0.255	-0.325
16	2.123	1.258	0.994	0.468	3.916	1.793	2.184	1.062	2.854	0.141	0.521	0.238	-0.251
17	2.415	2.074	1.181	0.489	4.020	1.606	2.504	1.207	2.813	0.161	0.535	0.214	-0.124
18	2.624	3.298	1.310	0.499	4.100	1.476	2.778	1.312	2.788	0.174	0.545	0.196	-0.035
19	2.936	6.120	1.346	0.459	4.376	1.440	3.039	1.468	2.908	0.195	0.582	0.191	0.070
20	3.034	8.501	1.303	0.430	4.517	1.483	3.045	1.517	3.000	0.202	0.601	0.197	0.093
21	3.074	10.201	1.260	0.410	4.601	1.526	3.014	1.537	3.064	0.204	0.612	0.203	0.098
22	3.094	13.601	1.174	0.379	4.707	1.613	2.918	1.547	3.160	0.206	0.626	0.214	0.088
23	3.037	17.001	1.130	0.372	4.693	1.656	2.834	1.518	3.174	0.202	0.624	0.220	0.062
24	2.977	18.701	1.102	0.370	4.662	1.685	2.767	1.488	3.173	0.198	0.620	0.224	0.038
25	2.984	20.401	1.087	0.364	4.684	1.699	2.756	1.492	3.191	0.198	0.623	0.226	0.038
26	2.865	23.189	1.058	0.369	4.593	1.728	2.658	1.433	3.161	0.190	0.611	0.230	-0.005

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-40-2

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	3.001 IN	W/C:	26.6 %	DRY DENSITY.	95.4 PCF
DIAMETER:	1.385 IN	GS:	2.72	VOID RATIO:	0.779

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.741 AT A STRESS OF 0.68 TSF
CONSOLIDATED TO A VOID RATIO OF 0.669 BY AN EFFECTIVE STRESS OF 2.81 TSF
REBOUNDED TO A VOID RATIO OF 0.690 BY AN EFFECTIVE STRESS OF 1.44 TSF
EQUIVALENT CONSOLIDATION STRESS, P_e, OF 6.588 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.947 IN	W/C:	26.1 %	CHAMBER PRESSURE:	8.68 TSF
DIAMETER:	1.339 IN	B-VALUE:	0.95	PORE PRESSURE:	7.24 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	1.440	1.440	1.000	0.000	1.440	0.000	0.219	0.219	-0.782
8	0.306	0.034	0.058	0.188	1.689	1.382	1.222	0.153	1.536	0.023	0.256	0.210	-0.674
9	0.714	0.068	0.101	0.141	2.054	1.339	1.534	0.357	1.696	0.054	0.312	0.203	-0.538
10	0.968	0.136	0.202	0.208	2.207	1.238	1.782	0.484	1.723	0.073	0.335	0.188	-0.439
11	1.220	0.271	0.252	0.207	2.408	1.188	2.027	0.610	1.798	0.093	0.365	0.180	-0.351
12	1.417	0.475	0.281	0.198	2.576	1.159	2.223	0.709	1.868	0.108	0.391	0.176	-0.283
13	1.537	0.679	0.295	0.192	2.682	1.145	2.343	0.769	1.913	0.117	0.407	0.174	-0.243
14	1.608	0.814	0.302	0.188	2.746	1.138	2.414	0.804	1.942	0.122	0.417	0.173	-0.219
15	1.699	1.086	0.317	0.186	2.823	1.123	2.513	0.850	1.973	0.129	0.428	0.170	-0.188
16	1.833	1.527	0.338	0.185	2.934	1.102	2.664	0.916	2.018	0.139	0.445	0.167	-0.142
17	1.959	2.070	0.353	0.180	3.046	1.087	2.802	0.980	2.067	0.149	0.462	0.165	-0.099
18	2.101	2.749	0.367	0.175	3.174	1.073	2.958	1.051	2.123	0.159	0.482	0.163	-0.052
19	2.278	4.106	0.360	0.158	3.358	1.080	3.109	1.139	2.219	0.173	0.510	0.164	0.002
20	2.384	5.260	0.338	0.142	3.486	1.102	3.164	1.192	2.294	0.181	0.529	0.167	0.032
21	2.487	6.787	0.295	0.119	3.632	1.145	3.172	1.244	2.388	0.189	0.551	0.174	0.056
22	2.584	10.180	0.173	0.067	3.851	1.267	3.039	1.292	2.559	0.196	0.585	0.192	0.064
23	2.576	13.573	0.094	0.036	3.922	1.346	2.913	1.288	2.634	0.196	0.595	0.204	0.047
24	2.553	16.966	0.043	0.017	3.950	1.397	2.828	1.277	2.673	0.194	0.600	0.212	0.031
25	2.500	18.867	0.043	0.017	3.897	1.397	2.790	1.250	2.647	0.190	0.591	0.212	0.014
26	2.419	21.547	0.007	0.003	3.852	1.433	2.688	1.209	2.642	0.184	0.585	0.217	-0.018

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-40-4

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	3.000 IN	W/C:	26.7 %	DRY DENSITY:	95.2 PCF
DIAMETER:	1.398 IN	GS:	2.72	VOID RATIO:	0.784

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.760 AT A STRESS OF 0.30 TSF

CONSOLIDATED TO A VOID RATIO OF 0.674 BY AN EFFECTIVE STRESS OF 2.79 TSF

REBOUNDED TO A VOID RATIO OF 0.719 BY AN EFFECTIVE STRESS OF 0.76 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 5.474 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.960 IN	W/C:	27.1 %	CHAMBER PRESSURE:	7.31 TSF
DIAMETER:	1.365 IN	B-VALUE:	0.95	PORE PRESSURE:	6.55 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	0.756	0.756	1.000	0.000	0.756	0.000	0.138	0.138	-0.568
8	0.295	0.034	0.029	0.098	1.022	0.727	1.406	0.148	0.875	0.027	0.187	0.133	-0.470
9	0.491	0.068	0.058	0.117	1.190	0.698	1.704	0.246	0.944	0.045	0.217	0.128	-0.403
10	0.638	0.135	0.108	0.169	1.286	0.648	1.984	0.319	0.967	0.058	0.235	0.118	-0.347
11	0.856	0.270	0.144	0.168	1.468	0.612	2.399	0.428	1.040	0.078	0.268	0.112	-0.272
12	1.023	0.473	0.180	0.176	1.599	0.576	2.777	0.512	1.088	0.093	0.292	0.105	-0.212
13	1.140	0.676	0.180	0.158	1.716	0.576	2.980	0.570	1.146	0.104	0.314	0.105	-0.175
14	1.210	0.811	0.180	0.149	1.786	0.576	3.101	0.605	1.181	0.111	0.326	0.105	-0.154
15	1.299	1.081	0.166	0.127	1.890	0.590	3.201	0.650	1.240	0.119	0.345	0.108	-0.128
16	1.383	1.520	0.144	0.104	1.995	0.612	3.260	0.692	1.304	0.126	0.364	0.112	-0.106
17	1.510	2.061	0.108	0.072	2.158	0.648	3.330	0.755	1.403	0.138	0.394	0.118	-0.072
18	1.605	2.736	0.072	0.045	2.289	0.684	3.347	0.803	1.487	0.147	0.418	0.125	-0.049
19	1.765	4.088	0.	0.	2.521	0.756	3.334	0.882	1.638	0.161	0.460	0.138	-0.012
20	1.856	5.236	-0.043	-0.023	2.655	0.799	3.322	0.928	1.727	0.170	0.485	0.146	0.009
21	1.905	6.757	-0.094	-0.049	2.755	0.850	3.243	0.953	1.802	0.174	0.503	0.155	0.015
22	1.995	10.135	-0.202	-0.101	2.952	0.958	3.083	0.997	1.955	0.182	0.539	0.175	0.023
23	2.005	13.514	-0.302	-0.151	3.063	1.058	2.894	1.002	2.061	0.183	0.560	0.193	0.008
24	1.967	16.892	-0.374	-0.190	3.097	1.130	2.740	0.983	2.114	0.180	0.566	0.206	-0.018
25	1.903	18.784	-0.425	-0.223	3.084	1.181	2.612	0.952	2.132	0.174	0.563	0.216	-0.047
26	1.887	21.453	-0.461	-0.244	3.104	1.217	2.551	0.944	2.160	0.172	0.567	0.222	-0.059

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-40-8

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	3.000 IN	W/C:	27.2 %	DRY DENSITY:	94.4 PCF
DIAMETER:	1.380 IN	GS:	2.72	VOID RATIO:	0.798

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.778 AT A STRESS OF 0.29 TSF
CONSOLIDATED TO A VOID RATIO OF 0.676 BY AN EFFECTIVE STRESS OF 2.87 TSF
REBOUNDED TO A VOID RATIO OF 0.743 BY AN EFFECTIVE STRESS OF 0.34 TSF
EQUIVALENT CONSOLIDATION STRESS, P_e, OF 4.723 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.965 IN	W/C:	27.7 %	CHAMBER PRESSURE:	2.54 TSF
DIAMETER:	1.353 IN	B-VALUE:	1.00	PORE PRESSURE:	2.20 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	0.338	0.338	1.000	0.000	0.338	0.000	0.072	0.072	-0.432
8	0.100	0.101	0.007	0.072	0.431	0.331	1.302	0.050	0.381	0.011	0.091	0.070	-0.399
9	0.100	0.101	0.029	0.288	0.409	0.310	1.323	0.050	0.360	0.011	0.087	0.066	-0.395
10	0.250	0.101	0.058	0.231	0.531	0.281	1.889	0.125	0.406	0.026	0.112	0.059	-0.343
11	0.374	0.135	0.072	0.192	0.641	0.266	2.405	0.187	0.454	0.040	0.136	0.056	-0.301
12	0.424	0.202	0.101	0.238	0.661	0.238	2.783	0.212	0.449	0.045	0.140	0.050	-0.280
13	0.622	0.304	0.130	0.208	0.831	0.209	3.978	0.311	0.520	0.066	0.176	0.044	-0.212
14	0.768	0.506	0.151	0.197	0.955	0.187	5.102	0.384	0.571	0.081	0.202	0.040	-0.162
15	0.934	0.877	0.130	0.139	1.143	0.209	5.474	0.467	0.676	0.099	0.242	0.044	-0.114
16	1.025	1.248	0.122	0.119	1.241	0.216	5.744	0.512	0.728	0.108	0.263	0.046	-0.087
17	1.176	2.057	0.050	0.043	1.464	0.288	5.083	0.588	0.876	0.124	0.310	0.061	-0.052
18	1.334	3.272	0.	0.	1.673	0.338	4.943	0.667	1.006	0.141	0.354	0.072	-0.012
19	1.547	6.071	-0.144	-0.093	2.029	0.482	4.207	0.773	1.256	0.164	0.430	0.102	0.029
20	1.620	8.432	-0.238	-0.147	2.196	0.576	3.813	0.810	1.386	0.172	0.465	0.122	0.034
21	1.645	10.118	-0.274	-0.166	2.257	0.612	3.688	0.822	1.434	0.174	0.478	0.130	0.036
22	1.683	13.491	-0.367	-0.218	2.388	0.706	3.385	0.841	1.547	0.178	0.506	0.149	0.030
23	1.670	16.863	-0.410	-0.246	2.419	0.749	3.230	0.835	1.584	0.177	0.512	0.159	0.018
24	1.677	18.550	-0.439	-0.262	2.455	0.778	3.157	0.839	1.616	0.178	0.520	0.165	0.015
25	1.665	20.236	-0.454	-0.272	2.457	0.792	3.102	0.832	1.624	0.176	0.520	0.168	0.009
26	1.611	23.002	-0.490	-0.304	2.439	0.828	2.945	0.805	1.633	0.171	0.516	0.175	-0.015

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-160-1

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	3.000 IN	W/C:	27.1 %	DRY DENSITY:	94.8 PCF
DIAMETER:	1.379 IN	GS:	2.72	VOID RATIO:	0.790

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.759 AT A STRESS OF 0.31 TSF

CONSOLIDATED TO A VOID RATIO OF 0.551 BY AN EFFECTIVE STRESS OF 11.44 TSF

REBOUNDED TO A VOID RATIO OF 0.551 BY AN EFFECTIVE STRESS OF 11.44 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 18.119 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.843 IN	W/C:	23.6 %	CHAMBER PRESSURE:	13.64 TSF
DIAMETER:	1.257 IN	B-VALUE:	0.99	PORE PRESSURE:	2.20 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFFCT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	11.434	11.434	1.000	0.000	11.434	0.000	0.631	0.631	-3.532
8	0.260	0.106	0.014	0.055	11.679	11.419	1.023	0.130	11.549	0.007	0.645	0.630	-3.447
9	0.608	0.106	0.036	0.059	12.005	11.398	1.053	0.304	11.701	0.017	0.663	0.629	-3.334
10	1.128	0.106	0.094	0.083	12.468	11.340	1.100	0.564	11.904	0.031	0.688	0.626	-3.159
11	1.532	0.141	0.144	0.094	12.822	11.290	1.136	0.766	12.056	0.042	0.708	0.623	-3.023
12	1.934	0.211	0.209	0.108	13.159	11.225	1.172	0.967	12.192	0.053	0.726	0.619	-2.884
13	2.938	0.317	0.475	0.162	13.896	10.958	1.268	1.469	12.427	0.081	0.767	0.605	-2.519
14	3.842	0.528	0.850	0.221	14.426	10.584	1.363	1.921	12.505	0.106	0.796	0.584	-2.165
15	4.749	0.915	1.642	0.346	14.541	9.792	1.485	2.374	12.166	0.131	0.802	0.540	-1.733
16	5.246	1.301	2.210	0.421	14.469	9.223	1.569	2.623	11.846	0.145	0.799	0.509	-1.471
17	6.149	2.146	3.283	0.534	14.299	8.150	1.754	3.074	11.225	0.170	0.789	0.450	-0.988
18	6.846	3.412	4.054	0.592	14.226	7.380	1.928	3.423	10.803	0.189	0.785	0.407	-0.626
19	7.769	6.331	4.853	0.625	14.350	6.581	2.181	3.885	10.465	0.214	0.792	0.363	-0.187
20	8.059	8.794	5.040	0.625	14.452	6.394	2.260	4.029	10.423	0.222	0.798	0.353	-0.061
21	8.238	10.552	5.054	0.614	14.617	6.379	2.291	4.119	10.498	0.227	0.807	0.352	-0.002
22	8.217	14.070	5.054	0.615	14.596	6.379	2.288	4.108	10.488	0.227	0.806	0.352	-0.009
23	8.103	17.587	5.105	0.630	14.431	6.329	2.280	4.051	10.380	0.224	0.796	0.349	-0.035
24	8.011	19.346	5.119	0.639	14.325	6.314	2.269	4.005	10.320	0.221	0.791	0.348	-0.062
25	7.929	21.104	5.134	0.647	14.229	6.300	2.259	3.964	10.264	0.219	0.785	0.348	-0.085
26	7.684	23.989	5.141	0.669	13.976	6.293	2.221	3.842	10.135	0.212	0.771	0.347	-0.161

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-160-2

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	2.998 IN	W/C:	27.1 %	DRY DENSITY:	94.6 PCF
DIAMETER:	1.384 IN	GS:	2.72	VOID RATIO:	0.796

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.769 AT A STRESS OF 0.26 TSF
CONSOLIDATED TO A VOID RATIO OF 0.552 BY AN EFFECTIVE STRESS OF 11.55 TSF
REBOUNDED TO A VOID RATIO OF 0.568 BY AN EFFECTIVE STRESS OF 5.78 TSF
EQUIVALENT CONSOLIDATION STRESS, P_e, OF 11.724 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.854 IN	W/C:	21.9 %	CHAMBER PRESSURE:	8.29 TSF
DIAMETER:	1.266 IN	B-VALUE:	1.00	PORE PRESSURE:	2.54 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	5.753	5.753	1.000	0.000	5.753	0.000	0.364	0.364	-2.300
8	0.342	0.140	0.043	0.126	6.052	5.710	1.060	0.171	5.881	0.011	0.383	0.361	-2.184
9	0.683	0.210	0.108	0.158	6.328	5.645	1.121	0.342	5.986	0.022	0.400	0.357	-2.065
10	1.166	0.280	0.259	0.222	6.659	5.494	1.212	0.583	6.076	0.037	0.421	0.348	-1.885
11	1.931	0.350	0.482	0.250	7.201	5.270	1.366	0.965	6.236	0.061	0.456	0.333	-1.603
12	2.323	0.456	0.576	0.248	7.500	5.177	1.449	1.161	6.338	0.073	0.475	0.328	-1.462
13	3.165	0.561	0.799	0.252	8.119	4.954	1.639	1.583	6.536	0.100	0.514	0.313	-1.155
14	3.663	0.701	0.842	0.230	8.574	4.910	1.746	1.832	6.742	0.116	0.542	0.311	-0.990
15	4.279	1.051	0.857	0.200	9.175	4.896	1.874	2.140	7.036	0.135	0.581	0.310	-0.794
16	4.608	1.402	0.871	0.189	9.490	4.882	1.944	2.304	7.186	0.146	0.600	0.309	-0.687
17	4.850	1.752	0.871	0.180	9.731	4.882	1.993	2.425	7.306	0.153	0.616	0.309	-0.611
18	5.060	2.102	0.922	0.182	9.891	4.831	2.047	2.530	7.361	0.160	0.626	0.306	-0.536
19	5.382	2.628	0.958	0.178	10.177	4.795	2.122	2.691	7.486	0.170	0.644	0.303	-0.428
20	5.733	3.504	1.051	0.183	10.434	4.702	2.219	2.866	7.568	0.181	0.660	0.297	-0.300
21	6.211	5.256	1.123	0.181	10.840	4.630	2.341	3.105	7.735	0.196	0.686	0.293	-0.136
22	6.349	7.008	1.130	0.178	10.971	4.622	2.373	3.174	7.797	0.201	0.694	0.292	-0.091
23	6.496	10.512	1.080	0.166	11.169	4.673	2.390	3.248	7.921	0.206	0.707	0.296	-0.054
24	6.420	14.541	0.950	0.148	11.223	4.802	2.337	3.210	8.012	0.203	0.710	0.304	-0.102
25	6.305	17.589	0.864	0.137	11.194	4.889	2.290	3.153	8.041	0.199	0.708	0.309	-0.154
26	6.129	21.058	0.835	0.136	11.047	4.918	2.246	3.065	7.982	0.194	0.699	0.311	-0.215

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-160-4(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	2.998 IN	W/C:	27.2 %	DRY DENSITY:	94.3 PCF
DIAMETER:	1.395 IN	GS:	2.72	VOID RATIO:	0.801

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.777 AT A STRESS OF 0.26 TSF

CONSOLIDATED TO A VOID RATIO OF 0.530 BY AN EFFECTIVE STRESS OF 11.38 TSF

REBOUNDED TO A VOID RATIO OF 0.587 BY AN EFFECTIVE STRESS OF 2.79 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 13.631 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.865 IN	W/C:	23.2 %	CHAMBER PRESSURE:	11.29 TSF
DIAMETER:	1.283 IN	B-VALUE:	0.82	PORE PRESSURE:	8.50 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	2.794	2.794	1.000	0.000	2.794	0.000	0.205	0.205	-1.583
8	0.333	0.140	0.036	0.108	3.091	2.758	1.121	0.166	2.924	0.012	0.227	0.202	-1.471
9	0.665	0.209	0.086	0.130	3.372	2.707	1.246	0.332	3.040	0.024	0.247	0.199	-1.357
10	1.024	0.279	0.194	0.190	3.623	2.599	1.394	0.512	3.111	0.038	0.266	0.191	-1.224
11	1.630	0.349	0.360	0.221	4.064	2.434	1.670	0.815	3.249	0.060	0.298	0.179	-1.003
12	1.819	0.454	0.396	0.218	4.217	2.398	1.759	0.910	3.307	0.067	0.309	0.176	-0.936
13	2.228	0.558	0.518	0.233	4.503	2.275	1.979	1.114	3.389	0.082	0.330	0.167	-0.785
14	2.523	0.698	0.526	0.208	4.791	2.268	2.112	1.261	3.529	0.093	0.351	0.166	-0.691
15	3.049	1.047	0.490	0.161	5.353	2.304	2.323	1.524	3.828	0.112	0.393	0.169	-0.532
16	3.404	1.396	0.439	0.129	5.759	2.354	2.446	1.702	4.057	0.125	0.422	0.173	-0.429
17	3.621	1.745	0.353	0.097	6.061	2.441	2.483	1.810	4.251	0.133	0.445	0.179	-0.377
18	3.780	2.094	0.302	0.080	6.271	2.491	2.517	1.890	4.381	0.139	0.460	0.183	-0.336
19	4.080	2.618	0.230	0.056	6.644	2.563	2.592	2.040	4.603	0.150	0.487	0.188	-0.255
20	4.393	3.490	0.151	0.034	7.035	2.642	2.662	2.196	4.839	0.161	0.516	0.194	-0.171
21	4.754	5.236	-0.043	-0.009	7.591	2.837	2.676	2.377	5.214	0.174	0.557	0.208	-0.093
22	4.962	6.981	-0.202	-0.041	7.957	2.995	2.657	2.481	5.476	0.182	0.584	0.220	-0.057
23	5.110	10.471	-0.410	-0.080	8.314	3.204	2.595	2.555	5.759	0.187	0.610	0.235	-0.049
24	5.083	14.485	-0.612	-0.120	8.488	3.406	2.493	2.541	5.947	0.186	0.623	0.250	-0.095
25	5.052	17.522	-0.727	-0.144	8.572	3.521	2.435	2.526	6.047	0.185	0.629	0.258	-0.126
26	4.932	20.977	-0.785	-0.159	8.510	3.578	2.378	2.466	6.044	0.181	0.624	0.263	-0.174

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-160-4(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	3.000 IN	W/C:	27.4 %	DRY DENSITY:	94.4 PCF
DIAMETER:	1.371 IN	GS:	2.72	VOID RATIO:	0.799

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.785 AT A STRESS OF 0.32 TSF

CONSOLIDATED TO A VOID RATIO OF 0.569 BY AN EFFECTIVE STRESS OF 11.45 TSF

REBOUNDED TO A VOID RATIO OF 0.598 BY AN EFFECTIVE STRESS OF 2.92 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 12.539 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.881 IN	W/C:	24,0 %	CHAMBER PRESSURE:	10.87 TSF
DIAMETER:	1.265 IN	B-VALUE:	0.86	PORE PRESSURE:	7.95 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	2.923	2.923	1.000	0.000	2.923	0.000	0.233	0.233	-1.521
8	0.029	0.069	0.007	0.252	2.945	2.916	1.010	0.014	2.930	0.001	0.235	0.233	-1.511
9	0.314	0.069	0.065	0.206	3.173	2.858	1.110	0.157	3.016	0.013	0.253	0.228	-1.410
10	1.027	0.139	0.151	0.147	3.799	2.772	1.371	0.514	3.286	0.041	0.303	0.221	-1.170
11	1.140	0.208	0.281	0.246	3.782	2.642	1.431	0.570	3.212	0.045	0.302	0.211	-1.110
12	1.310	0.243	0.281	0.214	3.952	2.642	1.496	0.655	3.297	0.052	0.315	0.211	-1.057
13	2.183	0.451	0.504	0.231	4.602	2.419	1.902	1.092	3.511	0.087	0.367	0.193	-0.740
14	2.893	0.902	0.590	0.204	5.225	2.333	2.240	1.446	3.779	0.115	0.417	0.186	-0.501
15	3.336	1.388	0.540	0.162	5.719	2.383	2.400	1.668	4.051	0.133	0.456	0.190	-0.371
16	3.459	1.978	0.454	0.131	5.928	2.470	2.401	1.729	4.199	0.138	0.473	0.197	-0.348
17	4.126	2.812	0.331	0.080	6.718	2.592	2.592	2.063	4.655	0.165	0.536	0.207	-0.160
18	4.532	4.443	0.173	0.038	7.282	2.750	2.648	2.266	5.016	0.181	0.581	0.219	-0.062
19	4.839	6.456	0.	0.	7.762	2.923	2.655	2.420	5.343	0.193	0.619	0.233	0.003
20	5.067	9.927	-0.238	-0.047	8.227	3.161	2.603	2.533	5.694	0.202	0.656	0.252	0.031
21	5.102	13.398	-0.367	-0.072	8.392	3.290	2.551	2.551	5.841	0.203	0.669	0.262	0.018
22	5.086	16.279	-0.454	-0.089	8.463	3.377	2.506	2.543	5.920	0.203	0.675	0.269	-0.003
23	4.987	19.195	-0.497	-0.100	8.407	3.420	2.458	2.494	5.914	0.199	0.670	0.273	-0.042
24	4.917	21.590	-0.540	-0.110	8.380	3.463	2.420	2.458	5.921	0.196	0.668	0.276	-0.073

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-160-8

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	3.000 ı	W/C:	27.4 %	DRY DENSITY:	94.1 PCF
DIAMETER:	1.375 IN	GS:	2.72	VOID RATIO:	0.804

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.761 AT A STRESS OF 0.23 TSF

CONSOLIDATED TO A VOID RATIO OF 0.533 BY AN EFFECTIVE STRESS OF 11.38 TSF

REBOUNDED TO A VOID RATIO OF 0.615 BY AN EFFECTIVE STRESS OF 1.35 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 11.054 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.895 IN	W/C:	25.0 %	CHAMBER PRESSURE:	9.48 TSF
DIAMETER:	1.273 IN	B-VALUE:	0.94	PORE PRESSURE:	8.02 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	1.454	1.454	1.000	0.000	1.454	0.000	0.132	0.132	-1.133
8	0.141	0.069	0.	0.	1.596	1.454	1.097	0.071	1.525	0.006	0.144	0.132	-1.089
9	0.311	0.069	0.050	0.162	1.715	1.404	1.221	0.155	1.559	0.014	0.155	0.127	-1.026
10	0.677	0.138	0.101	0.149	2.030	1.354	1.500	0.338	1.692	0.031	0.184	0.122	-0.902
11	0.929	0.207	0.202	0.217	2.182	1.253	1.742	0.465	1.717	0.042	0.197	0.113	-0.803
12	1.126	0.242	0.238	0.211	2.342	1.217	1.925	0.563	1.780	0.051	0.212	0.110	-0.735
13	1.317	0.449	0.382	0.290	2.389	1.073	2.227	0.658	1.731	0.060	0.216	0.097	-0.648
14	1.998	0.898	0.425	0.213	3.028	1.030	2.941	0.999	2.029	0.090	0.274	0.093	-0.425
15	2.307	1.382	0.374	0.162	3.387	1.080	3.136	1.154	2.234	0.104	0.306	0.098	-0.337
16	2.577	1.969	0.295	0.115	3.736	1.159	3.223	1.289	2.448	0.117	0.338	0.105	-0.267
17	2.905	2.798	0.144	0.050	4.216	1.310	3.217	1.453	2.763	0.131	0.381	0.119	-0.192
18	3.296	4.421	-0.065	-0.020	4.815	1.519	3.170	1.648	3.167	0.149	0.436	0.137	-0.107
19	3.552	6.425	-0.295	-0.083	5.302	1.750	3.030	1.776	3.526	0.161	0.480	0.158	-0.069
20	3.777	9.879	-0.569	-0.151	5.800	2.023	2.867	1.889	3.912	0.171	0.525	0.183	-0.049
21	3.841	13.333	-0.727	-0.189	6.023	2.182	2.761	1.921	4.102	0.174	0.545	0.197	-0.058
22	3.863	16.200	-0.835	-0.216	6.152	2.290	2.687	1.931	4.221	0.175	0.557	0.207	-0.071
23	3.804	19.102	-0.900	-0.237	6.159	2.354	2.616	1.902	4.257	0.172	0.557	0.213	-0.102
24	3.744	21.485	-0.958	-0.256	6.156	2.412	2.552	1.872	4.284	0.169	0.557	0.218	-0.131

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-160-16(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	2.998 IN	W/C:	27.2 %	DRY DENSITY:	94.7 PCF
DIAMETER:	1.397 IN	GS:	2.72	VOID RATIO:	0.793

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.769 AT A STRESS OF 0.22 TSF
CONSOLIDATED TO A VOID RATIO OF 0.527 BY AN EFFECTIVE STRESS OF 11.47 TSF
REBOUNDED TO A VOID RATIO OF 0.632 BY AN EFFECTIVE STRESS OF 0.72 TSF
EQUIVALENT CONSOLIDATION STRESS, P_e, OF 9.778 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.909 IN	W/C:	25.0 %	CHAMBER PRESSURE:	8.80 TSF
DIAMETER:	1.309 IN	B-VALUE:	0.89	PORE PRESSURE:	8.08 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	0.720	0.720	1.000	0.000	0.720	0.000	0.074	0.074	-0.898
8	0.214	0.138	0.036	0.169	0.898	0.684	1.312	0.107	0.791	0.011	0.092	0.070	-0.824
9	0.453	0.206	0.079	0.175	1.094	0.641	1.707	0.227	0.867	0.023	0.112	0.066	-0.740
10	0.719	0.275	0.144	0.200	1.295	0.576	2.248	0.359	0.935	0.037	0.132	0.059	-0.645
11	0.983	0.344	0.209	0.212	1.494	0.511	2.923	0.492	1.003	0.050	0.153	0.052	-0.549
12	1.061	0.447	0.202	0.190	1.579	0.518	3.046	0.530	1.049	0.054	0.161	0.053	-0.526
13	1.191	0.550	0.245	0.206	1.666	0.475	3.506	0.595	1.071	0.061	0.170	0.049	-0.477
14	1.319	0.688	0.245	0.186	1.794	0.475	3.776	0.660	1.135	0.067	0.184	0.049	-0.437
15	1.572	1.031	0.230	0.147	2.061	0.490	4.210	0.786	1.275	0.080	0.211	0.050	-0.360
16	1.768	1.375	0.202	0.114	2.287	0.518	4.411	0.884	1.403	0.090	0.234	0.053	-0.303
17	1.885	1.719	0.144	0.076	2.461	0.576	4.272	0.942	1.518	0.096	0.252	0.059	-0.277
18	2.051	2.063	0.108	0.053	2.663	0.612	4.351	1.025	1.637	0.105	0.272	0.063	-0.232
19	2.206	2.578	0.050	0.023	2.876	0.670	4.295	1.103	1.773	0.113	0.294	0.068	-0.194
20	2.465	3.438	-0.036	-0.015	3.221	0.756	4.261	1.233	1.989	0.126	0.329	0.077	-0.128
21	2.737	5.156	-0.259	-0.095	3.716	0.979	3.795	1.369	2.348	0.140	0.380	0.100	-0.084
22	2.893	6.875	-0.439	-0.152	4.053	1.159	3.496	1.447	2.606	0.148	0.414	0.119	-0.068
23	3.010	10.313	-0.670	-0.222	4.399	1.390	3.166	1.505	2.894	0.154	0.450	0.142	-0.074
24	3.076	14.266	-0.864	-0.281	4.660	1.584	2.942	1.538	3.122	0.157	0.477	0.162	-0.099
25	3.045	17.257	-0.972	-0.319	4.737	1.692	2.799	1.522	3.214	0.156	0.484	0.173	-0.119
26	3.007	20.660	-1.051	-0.350	4.778	1.771	2.698	1.504	3.275	0.154	0.489	0.181	-0.145

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-FS-27-160-16(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT:	2.996 IN	W/C:	27.3 %	DRY DENSITY:	94.1 PCF
DIAMETER:	1.374 IN	GS:	2.72	VOID RATIO:	0.804

TEST CONSOLIDATION HISTORY:

AFTER INUNDATION AND SATURATION, SPECIMEN HAD A VOID RATIO OF 0.776 AT A STRESS OF 0.33 TSF

CONSOLIDATED TO A VOID RATIO OF 0.568 BY AN EFFECTIVE STRESS OF 11.51 TSF

REBOUNDED TO A VOID RATIO OF 0.669 BY AN EFFECTIVE STRESS OF 0.73 TSF

EQUIVALENT CONSOLIDATION STRESS, P_e, OF 7.571 TSF

PRE-SHEAR CONDITIONS:

HEIGHT:	2.909 IN	W/C:	25.9 %	CHAMBER PRESSURE:	8.12 TSF
DIAMETER:	1.308 IN	B-VALUE:	0.98	PORE PRESSURE:	7.34 TSF

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	INDUCED PWP TSF	"A" PARAM	EFFECT σ_1 TSF	EFFECT σ_3 TSF	EFFECT σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	QERR q_{error} TSF
7	0.000	0.	0.	0.	0.778	0.778	1.000	0.000	0.778	0.000	0.103	0.103	-0.736
8	0.107	0.069	0.007	0.067	0.877	0.770	1.139	0.053	0.824	0.007	0.116	0.102	-0.701
9	0.374	0.138	0.079	0.212	1.072	0.698	1.535	0.187	0.885	0.025	0.142	0.092	-0.603
10	0.668	0.138	0.137	0.205	1.309	0.641	2.042	0.334	0.975	0.044	0.173	0.085	-0.500
11	0.720	0.206	0.122	0.170	1.375	0.655	2.099	0.360	1.015	0.048	0.182	0.087	-0.486
12	0.666	0.275	0.158	0.238	1.285	0.619	2.075	0.333	0.952	0.044	0.170	0.082	-0.497
13	0.932	0.309	0.180	0.193	1.529	0.598	2.559	0.466	1.063	0.062	0.202	0.079	-0.409
14	1.087	0.516	0.288	0.265	1.576	0.490	3.219	0.543	1.033	0.072	0.208	0.065	-0.340
15	1.470	0.963	0.310	0.211	1.938	0.468	4.142	0.735	1.203	0.097	0.256	0.062	-0.215
16	1.716	1.444	0.274	0.159	2.220	0.504	4.404	0.858	1.362	0.113	0.293	0.067	-0.145
17	1.926	2.028	0.216	0.112	2.488	0.562	4.430	0.963	1.525	0.127	0.329	0.074	-0.089
18	2.171	2.853	0.101	0.046	2.848	0.677	4.208	1.086	1.762	0.143	0.376	0.089	-0.033
19	2.465	4.469	-0.072	-0.029	3.315	0.850	3.901	1.232	2.082	0.163	0.438	0.112	0.027
20	2.668	6.463	-0.288	-0.108	3.734	1.066	3.504	1.334	2.400	0.176	0.493	0.141	0.051
21	2.871	9.900	-0.533	-0.186	4.182	1.310	3.191	1.436	2.746	0.190	0.552	0.173	0.070
22	2.929	13.338	-0.677	-0.231	4.383	1.454	3.014	1.464	2.919	0.193	0.579	0.192	0.061
23	2.960	16.1[illegible]	[illegible]792	-0.268	4.530	1.570	2.886	1.480	3.050	0.195	0.598	0.207	0.050
24	2.918	19.079	-0.850	-0.291	4.546	1.627	2.794	1.459	3.086	0.193	0.600	0.215	0.026
25	2.868	21.451	-0.914	-0.319	4.560	1.692	2.695	1.434	3.126	0.189	0.602	0.223	-0.002

APPENDIX VI

TRIAXIAL COMPRESSION TESTS ON UNSATURATED SPECIMENS

APPENDIX VI. TRIAXIAL COMPRESSION TESTS ON UNSATURATED SPECIMENS

Fifteen specimens which were compacted dry of optimum and sixteen specimens which were compacted wet of optimum were tested at the "as compacted" or natural water content condition. Results from these tests were referred to as "unsaturated" throughout the text although pore water may have drained from some specimens which were consolidated to high degrees of saturation by large applied stresses. These specimens were not treated with potassium chloride (KCl) prior to compaction.

Each specimen was identified using the nomenclature described below. For example, the identification code for specimen number TXS-0-DR-20-40-2(2) was:

TXS - Triaxial shear test

0 - Estimated value of solute suction, tsf, based upon the weight of KCl added to the pore water

DR - Specimen was tested at its natural water content

20 - Nominal water content of the test specimen, percent

40 - Applied isotropic stress used to consolidate the test specimen, psi (1 psi = 0.07 tsf = 6.9 kPa)

2 - Numerical value analogous to an overconsolidation ratio. For a value of 1, the specimen was sheared at the consolidation stress; for a value of 2, the specimen was rebounded to 1/2 of the consolidation stress prior to shear; for a value of 4, the specimen was rebounded to 1/4 of the consolidation stress prior to shear; etc.

(2) - Number of the test specimen which was subjected to that particular consolidation and rebound sequence prior to shear. (1) - first specimen, (2) - second specimen, etc.

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-10-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.995 IN GS: 2.72 WATER CONTENT: 19.5 %
DIAMETER: 2.869 IN DRY DENSITY: 87.9 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.931 SATURATION: 57 % SUCTION: 13.1 TSF
COMPRESSED TO A VOID RATIO OF 0.922 BY AN ISOTROPIC STRESS OF 0.76 TSF
SUCTION: 11.0 TSF SATURATION: 58 %
REBOUNDED TO A VOID RATIO OF 0.922 BY AN ISOTROPIC STRESS OF 0.76 TSF
SUCTION: 11.0 TSF SATURATION: 58 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.986 IN DIAMETER: 2.860 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 1.79 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 20.1 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.922	58	11.0	0.749	0.749	1.000	0.	0.749	0.	0.419	0.419	1.787	-0.278
11	0.538	0.050	0.065	0.921	58	8.6	1.323	0.785	1.685	0.269	1.054	0.150	0.736	0.437	1.797	-0.116
12	1.262	0.184	0.214	0.918	58	12.2	2.039	0.778	2.623	0.631	1.408	0.346	1.119	0.427	1.823	0.111
13	1.601	0.418	0.387	0.915	58	8.6	2.314	0.713	3.247	0.801	1.513	0.432	1.249	0.385	1.853	0.228
14	1.917	0.635	0.558	0.912	58	9.0	2.630	0.713	3.689	0.958	1.671	0.509	1.396	0.379	1.883	0.325
15	2.484	1.570	1.249	0.898	59	8.3	3.240	0.756	4.286	1.242	1.998	0.617	1.611	0.376	2.012	0.485
16	2.805	2.823	2.085	0.882	60	8.1	3.504	0.698	5.017	1.403	2.101	0.643	1.606	0.320	2.182	0.584
17	3.160	6.181	4.022	0.845	63	10.5	3.923	0.763	5.141	1.580	2.343	0.597	1.481	0.288	2.649	0.647
18	3.484	9.706	5.780	0.811	65	9.5	4.233	0.749	5.653	1.742	2.491	0.547	1.330	0.235	3.182	0.710
19	3.791	11.894	6.820	0.791	67	9.8	4.547	0.756	6.015	1.896	2.652	0.532	1.277	0.212	3.560	0.776
20	4.147	12.980	7.275	0.782	68	9.8	4.911	0.763	6.434	2.074	2.837	0.554	1.312	0.204	3.743	0.873
21	3.997	16.405	8.550	0.758	70	10.7	4.703	0.706	6.665	1.999	2.704	0.463	1.089	0.163	4.319	0.791

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-20-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.996 IN GS: 2.72 WATER CONTENT: 19.3 %
DIAMETER: 2.871 IN DRY DENSITY: 90.8 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.870 SATURATION: 60 % SUCTION: 15.3 TSF
COMPRESSED TO A VOID RATIO OF 0.848 BY AN ISOTROPIC STRESS OF 1.48 TSF
SUCTION: 11.2 TSF SATURATION: 62 %
REBOUNDED TO A VOID RATIO OF 0.848 BY AN ISOTROPIC STRESS OF 1.48 TSF
SUCTION: 11.2 TSF SATURATION: 62 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.975 IN DIAMETER: 2.847 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 2.61 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 19.4 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.848	62	11.2	1.483	1.483	1.000	0.	1.483	0.	0.570	0.570	2.603	-0.478
11	0.316	0.033	0.019	0.848	62	10.5	1.814	1.498	1.211	0.158	1.656	0.061	0.696	0.574	2.608	-0.381
12	1.016	0.100	0.051	0.847	62	11.2	2.463	1.447	1.702	0.508	1.955	0.194	0.942	0.553	2.616	-0.152
13	1.806	0.234	0.187	0.845	62	10.7	3.290	1.483	2.218	0.903	2.386	0.341	1.241	0.559	2.651	0.087
14	2.280	0.385	0.318	0.842	62	10.0	3.770	1.490	2.530	1.140	2.630	0.424	1.404	0.555	2.686	0.232
15	2.928	0.669	0.536	0.838	63	11.0	4.368	1.440	3.034	1.464	2.904	0.534	1.592	0.525	2.744	0.441
16	3.105	1.105	0.891	0.832	63	9.5	4.581	1.476	3.104	1.553	3.029	0.546	1.611	0.519	2.843	0.483
17	3.727	2.661	2.094	0.810	65	9.3	5.210	1.483	3.513	1.863	3.346	0.580	1.622	0.462	3.211	0.648
18	4.182	4.787	3.601	0.782	67	9.3	5.665	1.483	3.820	2.091	3.574	0.556	1.507	0.395	3.759	0.749
19	4.534	7.264	5.093	0.754	70	9.3	6.025	1.490	4.042	2.267	3.758	0.513	1.364	0.337	4.418	0.807
20	4.790	9.222	6.098	0.736	71	8.8	6.258	1.469	4.261	2.395	3.864	0.485	1.266	0.297	4.942	0.851
21	5.043	11.916	7.351	0.712	74	9.0	6.476	1.433	4.520	2.522	3.955	0.442	1.135	0.251	5.707	0.877
22	5.336	14.460	8.397	0.693	76	9.5	6.834	1.498	4.563	2.668	4.166	0.413	1.058	0.232	6.459	0.899
23	5.504	17.941	9.605	0.671	78	7.4	6.937	1.433	4.842	2.752	4.185	0.368	0.927	0.191	7.484	0.884

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-40-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.997 IN GS: 2.72 WATER CONTENT: 19.0 %
DIAMETER: 2.872 IN DRY DENSITY: 87.8 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.934 SATURATION: 55 % SUCTION: 16.2 TSF
COMPRESSED TO A VOID RATIO OF 0.824 BY AN ISOTROPIC STRESS OF 2.92 TSF
SUCTION: 5.2 TSF SATURATION: 63 %
REBOUNDED TO A VOID RATIO OF 0.824 BY AN ISOTROPIC STRESS OF 2.92 TSF
SUCTION: 5.2 TSF SATURATION: 63 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.909 IN DIAMETER: 2.747 IN
EQUIVALENT CONSOLIDATION STRESS, Pe: 2.97 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 19.4 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.824	63	5.2	2.930	2.930	1.000	0.	2.930	0.	0.988	0.988	2.966	-0.774
11	1.166	0.186	0.188	0.821	63	5.4	4.067	2.902	1.402	0.583	3.484	0.193	1.346	0.960	3.022	-0.406
12	2.893	1.303	1.347	0.799	65	5.2	5.823	2.930	1.987	1.446	4.377	0.426	1.713	0.862	3.398	0.103
13	3.892	2.031	2.104	0.786	66	3.7	6.808	2.916	2.335	1.946	4.862	0.529	1.852	0.793	3.676	0.399
14	4.811	2.809	2.836	0.772	67	3.8	7.727	2.916	2.650	2.406	5.322	0.606	1.946	0.734	3.970	0.666
15	5.314	3.909	3.772	0.755	68	3.8	8.244	2.930	2.813	2.657	5.587	0.605	1.878	0.668	4.390	0.788
16	5.512	5.145	4.718	0.738	70	3.9	8.392	2.880	2.914	2.756	5.636	0.566	1.723	0.591	4.871	0.823
17	5.456	6.735	5.694	0.720	72	3.7	8.351	2.894	2.885	2.728	5.623	0.502	1.536	0.532	5.436	0.758
18	5.874	7.836	6.379	0.708	73	6.6	8.754	2.880	3.039	2.937	5.817	0.499	1.488	0.490	5.881	0.857
19	6.205	9.156	7.150	0.694	75	5.9	9.135	2.930	3.117	3.102	6.033	0.482	1.419	0.455	6.437	0.909
20	6.403	10.679	7.981	0.678	76	4.5	9.298	2.894	3.212	3.202	6.096	0.450	1.308	0.407	7.110	0.926
21	6.581	11.592	8.437	0.670	77	5.7	9.461	2.880	3.285	3.291	6.171	0.438	1.259	0.383	7.515	0.953
22	6.801	13.014	9.104	0.658	79	3.9	9.674	2.873	3.367	3.401	6.273	0.417	1.185	0.352	8.161	0.973
23	7.034	14.740	9.834	0.645	80	4.2	9.950	2.916	3.412	3.517	6.433	0.393	1.112	0.326	8.947	0.977
24	7.138	15.806	10.230	0.637	81	4.7	10.032	2.894	3.466	3.569	6.463	0.379	1.066	0.308	9.413	0.977
25	7.238	17.363	10.744	0.628	82	3.9	10.104	2.866	3.526	3.619	6.485	0.360	1.004	0.285	10.060	0.963

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-80-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.995 IN GS: 2.72 WATER CONTENT: 19.2 %
DIAMETER: 2.863 IN DRY DENSITY: 90.7 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.873 SATURATION: 60 % SUCTION: 7.6 TSF
COMPRESSED TO A VOID RATIO OF 0.645 BY AN ISOTROPIC STRESS OF 5.77 TSF
SUCTION: 3.6 TSF SATURATION: 81 %
REBOUNDED TO A VOID RATIO OF 0.645 BY AN ISOTROPIC STRESS OF 5.77 TSF
SUCTION: 3.6 TSF SATURATION: 81 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.795 IN DIAMETER: 2.597 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 8.92 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 19.7 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.645	81	3.6	5.760	5.760	1.000	0.	5.760	0.	0.643	0.643	8.952	-1.766
11	1.632	0.138	0.129	0.642	81	3.8	7.414	5.782	1.282	0.816	6.598	0.090	0.816	0.636	9.085	-1.266
12	3.935	0.811	0.689	0.633	82	3.6	9.709	5.774	1.681	1.967	7.742	0.203	1.001	0.596	9.696	-0.587
13	6.162	2.174	1.669	0.617	85	5.4	11.951	5.789	2.065	3.081	8.870	0.283	1.098	0.532	10.887	0.019
14	7.564	3.986	2.670	0.601	87	3.0	13.339	5.774	2.310	3.782	9.557	0.308	1.085	0.470	12.295	0.353
15	7.312	5.280	3.172	0.592	88	3.4	13.079	5.767	2.268	3.656	9.423	0.279	1.000	0.441	13.084	0.213
16	7.645	7.921	3.899	0.580	90	3.2	13.420	5.774	2.324	3.823	9.597	0.267	0.936	0.403	14.342	0.219
17	7.624	10.457	4.289	0.574	91	3.1	13.405	5.782	2.319	3.812	9.593	0.253	0.889	0.383	15.077	0.153
18	7.837	13.201	4.571	0.569	92	2.4	13.611	5.774	2.357	3.918	9.693	0.251	0.871	0.369	15.636	0.178
19	7.816	17.826	4.782	0.566	92	2.3	13.597	5.782	2.352	3.908	9.689	0.243	0.846	0.360	16.072	0.136
20	7.406	21.864	4.850	0.565	92	2.5	13.188	5.782	2.281	3.703	9.485	0.228	0.813	0.357	16.215	-0.005
21	7.050	26.178	4.882	0.564	93	1.7	12.832	5.782	2.219	3.525	9.307	0.216	0.788	0.355	16.285	-0.122

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-160-1(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 6.005 IN GS: 2.72 WATER CONTENT: 19.4 %
DIAMETER: 2.871 IN DRY DENSITY: 91.1 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.864 SATURATION: 61 % SUCTION: 6.2 TSF
COMPRESSED TO A VOID RATIO OF 0.552 BY AN ISOTROPIC STRESS OF 11.48 TSF
SUCTION: 0.4 TSF SATURATION: 95 %
REBOUNDED TO A VOID RATIO OF 0.552 BY AN ISOTROPIC STRESS OF 11.48 TSF
SUCTION: 0.4 TSF SATURATION: 95 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.680 IN DIAMETER: 2.512 IN
EQUIVALENT CONSOLIDATION STRESS, Pe: 17.97 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 18.5 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.552	96	0.4	11.477	11.477	1.000	0.	11.477	0.	0.636	0.636	18.040	-3.534
11	0.785	0.035	0.049	0.551	96	0.8	12.261	11.477	1.068	0.392	11.869	0.022	0.675	0.632	18.152	-3.296
12	4.294	0.229	0.163	0.549	96	0.4	15.778	11.484	1.374	2.147	13.631	0.117	0.857	0.624	18.417	-2.212
13	7.767	0.669	0.383	0.546	97	0.1	19.236	11.470	1.677	3.883	15.353	0.205	1.016	0.606	18.940	-1.156
14	10.350	1.585	0.765	0.540	98	0.7	21.820	11.470	1.902	5.175	16.645	0.260	1.097	0.577	19.894	-0.417
15	10.553	2.887	1.150	0.534	99	0.6	22.030	11.477	1.920	5.277	16.753	0.252	1.053	0.549	20.917	-0.435
16	10.655	4.877	1.517	0.528	100	0.6	22.132	11.477	1.928	5.328	16.804	0.243	1.008	0.523	21.948	-0.483
17	10.951	7.729	1.844	0.523	100+	1.2	22.449	11.498	1.952	5.475	16.974	0.239	0.979	0.502	22.922	-0.470
18	12.653	9.754	2.159	0.518	100+	0.8	24.129	11.477	2.102	6.326	17.803	0.265	1.009	0.480	23.913	-0.008
19	12.074	11.250	2.275	0.516	100+	0.2	23.543	11.470	2.053	6.037	17.506	0.249	0.969	0.472	24.291	-0.218
20	12.350	14.225	2.407	0.514	100+	1.4	23.820	11.470	2.077	6.175	17.645	0.250	0.963	0.464	24.727	-0.165
21	11.818	16.338	2.485	0.513	100+	0.4	23.295	11.477	2.030	5.909	17.386	0.236	0.932	0.459	24.989	-0.355
22	11.112	20.599	2.583	0.511	100+	0.5	22.589	11.477	1.968	5.556	17.033	0.219	0.892	0.453	25.328	-0.604

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-160-1(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.996 IN GS: 2.72 WATER CONTENT: 19.1 %
DIAMETER: 2.869 IN DRY DENSITY: 89.4 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.899 SATURATION: 91 % SUCTION: 17.9 TSF
COMPRESSED TO A VOID RATIO OF 0.572 BY AN ISOTROPIC STRESS OF 11.53 TSF
SUCTION: 1.3 TSF SATURATION: 91 %
REBOUNDED TO A VOID RATIO OF 0.572 BY AN ISOTROPIC STRESS OF 11.53 TSF
SUCTION: 1.3 TSF SATURATION: 91 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.688 IN DIAMETER: 2.487 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 15.31 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 18.3 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.572	91	1.3	11.527	11.527	1.000	0.	11.527	0.	0.755	0.755	15.269	-3.327
11	2.248	0.123	0.075	0.571	91	1.1	13.776	11.527	1.195	1.124	12.651	0.073	0.894	0.748	15.411	-2.629
12	5.254	0.369	0.218	0.569	91	0.9	16.781	11.527	1.456	2.627	14.154	0.167	1.070	0.735	15.687	-1.704
13	7.881	0.756	0.437	0.565	92	0.8	19.401	11.520	1.684	3.941	15.461	0.244	1.203	0.715	16.122	-0.909
14	10.168	1.494	0.749	0.561	93	0.1	21.688	11.520	1.883	5.084	16.604	0.303	1.294	0.687	16.766	-0.239
15	10.528	2.496	1.088	0.555	94	0.6	22.048	11.520	1.914	5.264	16.784	0.301	1.260	0.658	17.503	-0.184
16	10.576	4.044	1.437	0.550	94	1.1	22.103	11.527	1.918	5.288	16.815	0.289	1.208	0.630	18.303	-0.232
17	10.880	5.995	1.747	0.545	95	0.7	22.407	11.527	1.944	5.440	16.967	0.286	1.176	0.605	19.048	-0.195
18	11.305	8.193	2.003	0.541	96	0.1	22.825	11.520	1.981	5.652	17.172	0.287	1.159	0.585	19.696	-0.110
19	11.649	10.232	2.189	0.538	97	0.1	23.162	11.513	2.012	5.825	17.337	0.289	1.148	0.570	20.182	-0.039
20	11.142	15.014	2.387	0.535	97	0.0	22.655	11.513	1.968	5.571	17.084	0.269	1.094	0.556	20.716	-0.240
21	11.116	18.970	2.514	0.533	98	0.0	22.622	11.506	1.966	5.558	17.064	0.264	1.074	0.546	21.068	-0.274
22	9.895	26.688	2.597	0.532	98	0.0	21.401	11.506	1.860	4.948	16.453	0.232	1.005	0.540	21.301	-0.677

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-40-2(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT: 6.003 IN GS: 2.72 WATER CONTENT: 19.5 %
DIAMETER: 2.871 IN DRY DENSITY: 93.0 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.825 SATURATION: 64 % SUCTION: 13.1 TSF
COMPRESSED TO A VOID RATIO OF 0.756 BY AN ISOTROPIC STRESS OF 2.87 TSF
SUCTION: **** TSF SATURATION: 70 %
REBOUNDED TO A VOID RATIO OF 0.763 BY AN ISOTROPIC STRESS OF 1.43 TSF
SUCTION: **** TSF SATURATION: 69 %

PRE-SHEAR CONDITIONS:

HEIGHT: 5.948 IN DIAMETER: 2.799 IN
EQUIVALENT CONSOLIDATION STRESS, Pe: 4.19 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 19.9 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.763	70	****	1.462	1.462	1.000	0.	1.462	0.	0.349	0.349	4.193	-0.598
11	0.519	0.017	0.001	0.763	70	****	1.916	1.397	1.372	0.260	1.656	0.062	0.457	0.333	4.194	-0.423
12	1.311	0.034	0.014	0.763	70	****	2.715	1.404	1.934	0.655	2.059	0.156	0.647	0.334	4.199	-0.175
13	2.083	0.084	0.052	0.762	70	****	3.573	1.490	2.397	1.041	2.532	0.247	0.848	0.354	4.216	0.051
14	1.842	0.118	0.065	0.762	70	****	3.310	1.469	2.254	0.921	2.390	0.218	0.784	0.348	4.222	-0.022
15	2.005	0.235	0.096	0.761	70	****	3.452	1.447	2.386	1.003	2.450	0.237	0.815	0.342	4.235	0.033
16	2.627	0.454	0.192	0.760	70	****	4.031	1.404	2.871	1.313	2.717	0.307	0.942	0.328	4.278	0.233
17	3.036	0.757	0.339	0.757	70	****	4.483	1.447	3.098	1.518	2.965	0.349	1.032	0.333	4.344	0.349
18	3.171	1.177	0.528	0.754	70	****	4.568	1.397	3.270	1.586	2.982	0.358	1.031	0.315	4.431	0.394
19	3.478	1.748	0.808	0.749	71	****	4.882	1.404	3.477	1.739	3.143	0.381	1.070	0.308	4.564	0.479
20	3.783	2.623	1.246	0.741	72	****	5.202	1.418	3.667	1.892	3.310	0.396	1.088	0.297	4.782	0.555
21	4.177	3.816	1.883	0.730	73	****	5.639	1.462	3.858	2.099	3.550	0.408	1.101	0.285	5.122	0.645
22	4.411	5.565	2.725	0.715	74	****	5.851	1.440	4.063	2.205	3.645	0.393	1.041	0.256	5.618	0.684
23	4.432	6.406	3.041	0.709	75	****	5.836	1.404	4.157	2.216	3.620	0.381	1.003	0.241	5.819	0.681
24	4.692	7.734	3.591	0.700	76	****	6.132	1.440	4.258	2.346	3.786	0.379	0.990	0.233	6.191	0.727
25	4.806	8.843	4.011	0.692	77	****	6.261	1.454	4.305	2.403	3.858	0.370	0.964	0.224	6.494	0.737
26	4.915	10.844	4.700	0.680	78	****	6.355	1.440	4.413	2.457	3.897	0.349	0.904	0.205	7.032	0.732
27	4.979	13.450	5.528	0.665	80	****	6.455	1.476	4.373	2.489	3.965	0.321	0.833	0.190	7.753	0.689
28	5.155	17.165	6.559	0.647	82	****	6.566	1.411	4.653	2.577	3.989	0.294	0.748	0.161	8.781	0.676

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-40-2(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT: 5.994 IN GS: 2.72 WATER CONTENT: 19.1 %

DIAMETER: 2.869 IN DRY DENSITY: [illegible]9.6 PCF

APPLIED STRESS HISTORY:

INITIAL SPECIMEN CONDITIONS:

VOID RATIO: 0.895 SATURATION: 58 % SUCTION: 14.3 TSF

COMPRESSED TO A VOID RATIO OF 0.784 BY AN ISOTROPIC STRESS OF 2.91 TSF

SUCTION: 5.7 TSF SATURATION: 66 %

REBOUNDED TO A VOID RATIO OF 0.789 BY AN ISOTROPIC STRESS OF 1.47 TSF

SUCTION: 3.1 TSF SATURATION: 66 %

PRE-SHEAR CONDITIONS:

HEIGHT: 5.921 IN DIAMETER: 2.740 IN

EQUIVALENT CONSOLIDATION STRESS, P_e: 3.60 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 19.7 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.789	66	3.1	1.469	1.469	1.000	0.	1.469	0.	0.408	0.408	3.601	-0.553
11	0.386	0.034	0.002	0.789	66	3.9	1.862	1.476	1.262	0.193	1.669	0.054	0.517	0.410	3.602	-0.433
12	1.327	0.084	0.024	0.789	66	3.8	2.803	1.476	1.899	0.663	2.139	0.184	0.777	0.409	3.609	-0.137
13	1.606	0.135	0.039	0.789	66	2.9	3.082	1.476	2.088	0.803	2.279	0.222	0.852	0.408	3.615	-0.050
14	1.878	0.236	0.064	0.788	66	2.8	3.332	1.454	2.291	0.939	2.393	0.259	0.919	0.401	3.624	0.039
15	2.621	0.490	0.170	0.786	66	2.6	4.068	1.447	2.811	1.310	2.757	0.358	1.110	0.395	3.664	0.271
16	3.213	1.013	0.443	0.781	66	3.0	4.704	1.490	3.156	1.607	3.097	0.426	1.248	0.396	3.768	0.442
17	3.733	2.246	1.144	0.769	68	3.3	5.223	1.490	3.505	1.866	3.357	0.461	1.289	0.368	4.052	0.583
18	3.992	3.952	2.049	0.753	69	2.6	5.439	1.447	3.758	1.996	3.443	0.448	1.220	0.325	4.459	0.641
19	4.347	5.725	2.929	0.737	71	2.9	5.809	1.462	3.974	2.174	3.635	0.443	1.184	0.298	4.904	0.715
20	4.612	8.056	3.985	0.718	72	2.6	6.110	1.498	4.080	2.306	3.804	0.418	1.108	0.272	5.512	0.745
21	4.986	10.302	4.887	0.702	74	3.1	6.440	1.454	4.428	2.493	3.947	0.408	1.055	0.238	6.106	0.824
22	5.047	13.224	5.955	0.683	76	2.8	6.494	1.447	4.487	2.523	3.970	0.365	0.939	0.209	6.913	0.781
23	5.213	17.210	7.159	0.661	79	2.9	6.704	1.490	4.498	2.607	4.097	0.326	0.840	0.187	7.985	0.742

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-40-4(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.996 IN GS: 2.72 WATER CONTENT: 19.5 %
DIAMETER: 2.868 IN DRY DENSITY: 89.9 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.889 SATURATION: 60 % SUCTION: 16.7 TSF
COMPRESSED TO A VOID RATIO OF 0.793 BY AN ISOTROPIC STRESS OF 2.91 TSF
SUCTION: 7.6 TSF SATURATION: 67 %
REBOUNDED TO A VOID RATIO OF 0.808 BY AN ISOTROPIC STRESS OF 0.73 TSF
SUCTION: 4.7 TSF SATURATION: 66 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.934 IN DIAMETER: 2.773 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 3.24 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 19.9 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.808	66	4.7	0.720	0.720	1.000	0.	0.720	0.	0.223	0.223	3.234	-0.386
11	0.302	0.034	0.002	0.808	66	3.7	1.029	0.727	1.415	0.151	0.878	0.047	0.318	0.225	3.234	-0.292
12	1.293	0.084	0.041	0.808	66	5.0	2.056	0.763	2.694	0.647	1.410	0.199	0.633	0.235	3.247	0.012
13	1.464	0.152	0.063	0.807	66	4.0	2.227	0.763	2.918	0.732	1.495	0.225	0.684	0.235	3.254	0.066
14	1.973	0.286	0.084	0.807	66	3.9	2.671	0.698	3.825	0.986	1.685	0.302	0.819	0.214	3.261	0.237
15	2.508	0.522	0.147	0.806	66	4.2	3.264	0.756	4.318	1.254	2.010	0.382	0.995	0.230	3.282	0.394
16	2.567	0.775	0.188	0.805	66	3.4	3.294	0.727	4.530	1.284	2.011	0.390	1.000	0.221	3.296	0.416
17	3.183	1 871	0.561	0.798	66	3.8	3.946	0.763	5.171	1.592	2.355	0.465	1.153	0.223	3.423	0.594
18	4.510	15.757	5.141	0.715	74	3.7	5.222	0.713	7.327	2.255	2.968	0.402	0.932	0.127	5.602	0.851
19	4.597	18.284	5.766	0.704	75	4.2	5.310	0.713	7.449	2.298	3.011	0.382	0.882	0.118	6.018	0.846

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-40-4(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.997 IN GS: 2.72 WATER CONTENT: 19.7 %
DIAMETER: 2.870 IN DRY DENSITY: 88.5 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.919 SATURATION: 58 % SUCTION: 15.6 TSF
COMPRESSED TO A VOID RATIO OF 0.797 BY AN ISOTROPIC STRESS OF 2.91 TSF
SUCTION: 5.2 TSF SATURATION: 67 %
REBOUNDED TO A VOID RATIO OF 0.808 BY AN ISOTROPIC STRESS OF 0.73 TSF
SUCTION: 4.3 TSF SATURATION: 66 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.921 IN DIAMETER: 2.737 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 3.24 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 20.5 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.808	66	4.3	0.727	0.727	1.000	0.	0.727	0.	0.225	0.225	3.233	-0.387
11	1.168	0.051	0.039	0.808	66	4.0	1.924	0.756	2.545	0.584	1.340	0.180	0.593	0.233	3.245	-0.026
12	1.417	0.169	0.053	0.807	66	3.9	2.130	0.713	2.988	0.708	1.421	0.218	0.655	0.219	3.250	0.060
13	2.095	0.439	0.078	0.807	66	3.8	2.815	0.720	3.910	1.048	1.768	0.322	0.864	0.221	3.258	0.272
14	2.746	0.980	0.205	0.805	67	3.9	3.466	0.720	4.813	1.373	2.093	0.416	1.050	0.218	[illegible].300	0.474
15	3.310	2.229	0.630	0.797	67	3.8	4.030	0.720	5.597	1.655	2.375	0.480	1.169	0.209	3.446	0.640
16	3.826	5.996	2.030	0.772	69	3.8	4.618	0.792	5.831	1.913	2.705	0.480	1.159	0.199	3.984	0.747
17	4.152	10.488	3.422	0.746	72	3.7	4.880	0.727	6.710	2.076	2.803	0.449	1.055	0.157	4.625	0.812
18	4.427	13.511	4.380	0.729	73	3.8	5.125	0.698	7.338	2.213	2.912	0.431	0.997	0.136	5.140	0.863
19	4.655	17.193	5.373	0.711	75	3.7	5.361	0.706	7.597	2.328	3.033	0.405	0.932	0.123	5.750	0.886
20	4.734	20.199	6.041	0.699	77	3.4	5.404	0.670	8.070	2.367	3.037	0.381	0.870	0.108	6.211	0.882
21	4.582	27.514	7.113	0.680	79	3.7	5.309	0.727	7.301	2.291	3.018	0.325	0.753	0.103	7.048	0.758

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-160-2

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 6.001 IN GS: 2.72 WATER CONTENT: 19.0 %
DIAMETER: 2.871 IN DRY DENSITY: 87.5 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.941 SATURATION: 55 % SUCTION: 7.8 TSF
COMPRESSED TO A VOID RATIO OF 0.570 BY AN ISOTROPIC STRESS OF 11.52 TSF
SUCTION: 1.1 TSF SATURATION: 91 %
REBOUNDED TO A VOID RATIO OF 0.582 BY AN ISOTROPIC STRESS OF 5.76 TSF
SUCTION: 2.1 TSF SATURATION: 89 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.659 IN DIAMETER: 2.462 IN
EQUIVALENT CONSOLIDATION STRESS, Pe: 14.17 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 19.2 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.582	89	2.1	5.774	5.774	1.000	0.	5.774	0.	0.407	0.407	14.181	-2.177
11	1.692	0.053	0.017	0.582	89	1.9	7.445	5.753	1.294	0.846	6.599	0.060	0.524	0.405	14.211	-1.642
12	3.903	0.141	0.043	0.581	89	1.2	9.656	5.753	1.679	1.952	7.704	0.137	0.677	0.404	14.257	-0.950
13	4.375	0.300	0.062	0.581	89	1.7	10.142	5.767	1.759	2.187	7.955	0.153	0.710	0.404	14.290	-0.806
14	5.979	0.742	0.130	0.580	89	2.1	11.754	5.774	2.036	2.990	8.764	0.208	0.816	0.401	14.408	-0.311
15	6.909	1.820	0.266	0.578	89	1.0	12.669	5.760	2.199	3.454	9.214	0.236	0.865	0.393	14.652	-0.035
16	7.889	4.630	0.579	0.573	90	0.5	13.663	5.774	2.366	3.945	9.719	0.259	0.897	0.379	15.229	0.226
17	8.188	8.093	0.807	0.569	91	1.1	13.941	5.753	2.423	4.094	9.847	0.261	0.890	0.367	15.669	0.290
18	8.432	13.748	1.008	0.566	91	0.8	14.185	5.753	2.466	4.216	9.969	0.262	0.883	0.358	16.069	0.335
19	8.349	18.007	1.079	0.565	92	0.8	14.109	5.760	2.450	4.175	9.935	0.257	0.870	0.355	16.214	0.297

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-160-4(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.997 IN GS: 2.72 WATER CONTENT: 19.4 %
DIAMETER: 2.870 IN DRY DENSITY: 91.4 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.858 SATURATION: 61 % SUCTION: 13.4 TSF
COMPRESSED TO A VOID RATIO OF 0.560 BY AN ISOTROPIC STRESS OF 11.51 TSF
SUCTION: 1.6 TSF SATURATION: 94 %
REBOUNDED TO A VOID RATIO OF 0.592 BY AN ISOTROPIC STRESS OF 2.87 TSF
SUCTION: 3.2 TSF SATURATION: 89 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.724 IN DIAMETER: 2.566 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 13.12 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 19.5 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.592	89	3.2	2.866	2.866	1.000	0.	2.866	0.	0.218	0.218	13.145	-1.558
11	1.337	0.035	0.042	0.591	89	2.7	4.195	2.858	1.468	0.669	3.527	0.051	0.318	0.216	13.212	-1.141
12	2.794	0.122	0.074	0.591	89	2.3	5.652	2.858	1.977	1.397	4.255	0.105	0.426	0.215	13.264	-0.686
13	3.729	0.245	0.116	0.590	89	2.6	6.595	2.866	2.301	1.865	4.730	0.140	0.495	0.215	13.332	-0.398
14	4.156	0.402	0.148	0.589	90	2.5	7.000	2.844	2.461	2.078	4.922	0.155	0.523	0.213	13.383	-0.264
15	4.878	0.631	0.188	0.589	90	3.1	7.714	2.837	2.719	2.439	5.276	0.181	0.574	0.211	13.449	-0.040
16	5.538	1.153	0.224	0.588	90	3.2	8.367	2.830	2.957	2.769	5.598	0.205	0.619	0.209	13.508	0.165
17	6.517	2.930	0.344	0.586	90	3.0	9.346	2.830	3.303	3.258	6.088	0.238	0.682	0.206	13.707	0.457
18	7.225	5.940	0.530	0.583	90	3.2	10.062	2.837	3.547	3.612	6.449	0.258	0.718	0.202	14.022	0.654
19	7.572	10.150	0.707	0.580	91	3.2	10.423	2.85[illegible]	3.656	3.786	6.637	0.264	0.727	0.199	14.331	0.737
20	7.527	16.552	0.902	0.577	91	2.1	10.371	2.844	3.647	3.763	6.607	0.256	0.706	0.194	14.681	0.697
21	7.060	24.092	0.987	0.576	92	3.1	9.904	2.844	3.483	3.530	6.374	0.238	0.668	0.192	14.837	0.538

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-160-8(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:

HEIGHT: 5.992 IN GS: 2.72 WATER CONTENT: 19.3 %

DIAMETER: 2.870 IN DRY DENSITY: 87.9 PCF

APPLIED STRESS HISTORY:

INITIAL SPECIMEN CONDITIONS:

VOID RATIO: 0.932 SATURATION: 56 % SUCTION: 7.8 TSF

COMPRESSED TO A VOID RATIO OF 0.571 BY AN ISOTROPIC STRESS OF 11.51 TSF

SUCTION: 1.5 TSF SATURATION: 92 %

REBOUNDED TO A VOID RATIO OF 0.601 BY AN ISOTROPIC STRESS OF 1.46 TSF

SUCTION: 3.4 TSF SATURATION: 87 %

PRE-SHEAR CONDITIONS:

HEIGHT: 5.719 IN DIAMETER: 2.474 IN

EQUIVALENT CONSOLIDATION STRESS, P_e: 12.26 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 20.0 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.601	87	3.4	1.462	1.462	1.000	0.	1.462	0.	0.119	0.119	12.277	-1.230
11	0.507	0.052	0.004	0.601	87	2.9	2.005	1.498	1.339	0.254	1.751	0.021	0.163	0.122	12.283	-1.078
12	1.405	0.122	0.016	0.601	87	3.5	2.859	1.454	1.966	0.702	2.157	0.057	0.232	0.118	12.301	-0.789
13	2.086	0.210	0.023	0.600	87	2.0	3.555	1.469	2.420	1.043	2.512	0.085	0.289	0.119	12.311	-0.577
14	2.865	0.297	0.037	0.600	87	2.3	4.326	1.462	2.960	1.432	2.894	0.116	0.351	0.119	12.331	-0.332
15	3.419	0.472	0.037	0.600	87	2.8	4.873	1.454	3.351	1.709	3.164	0.139	0.395	0.118	12.332	-0.157
16	4.181	0.734	0.038	0.600	87	3.2	5.621	1.440	3.904	2.091	3.531	0.170	0.456	0.117	12.333	0.086
17	4.970	1.276	0.047	0.600	87	1.5	6.417	1.447	4.434	2.485	3.932	0.201	0.520	0.117	12.347	0.332
18	5.452	1.696	0.040	0.600	87	1.8	6.907	1.454	4.749	2.726	4.181	0.221	0.560	0.118	12.336	0.484
19	6.066	2.745	0.056	0.600	88	4.5	7.520	1.454	5.171	3.033	4.487	0.245	0.608	0.118	12.360	0.675
20	6.534	4.511	0.062	0.600	88	2.5	7.989	1.454	5.493	3.267	4.721	0.264	0.646	0.118	12.368	0.822
21	6.794	7.291	0.134	0.599	88	1.9	8.277	1.483	5.581	3.397	4.880	0.272	0.663	0.119	12.476	0.890
22	7.046	9.704	0.211	0.597	88	1.4	8.507	1.462	5.820	3.523	4.984	0.280	0.676	0.116	12.592	0.964
23	7.145	12.974	0.248	0.597	88	2.1	8.599	1.454	5.913	3.572	5.027	0.282	0.680	0.115	12.649	0.992
24	7.162	16.384	0.383	0.595	88	3.7	8.638	1.476	5.852	3.581	5.057	0.279	0.672	0.115	12.857	0.977
25	7.178	18.989	0.422	0.594	88	4.2	8.632	1.454	5.935	3.589	5.043	0.278	0.668	0.113	12.917	0.982

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-160-8(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.997 IN GS: 2.72 WATER CONTENT: 19.6 %
DIAMETER: 2.870 IN DRY DENSITY: 89.9 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.890 SATURATION: 60 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.572 BY AN ISOTROPIC STRESS OF 11.52 TSF
SUCTION: **** TSF SATURATION: 93 %
REBOUNDED TO A VOID RATIO OF 0.607 BY AN ISOTROPIC STRESS OF 1.45 TSF
SUCTION: **** TSF SATURATION: 88 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.738 IN DIAMETER: 2.538 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 11.72 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 20.1 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.607	88	****	1.454	1.454	1.000	0.	1.454	0.	0.124	0.124	11.752	-1.188
11	1.103	0.087	0.019	0.606	88	****	2.550	1.447	1.762	0.552	1.999	0.047	0.216	0.123	11.779	-0.841
12	2.101	0.227	0.043	0.606	88	****	3.548	1.447	2.452	1.050	2.498	0.089	0.300	0.123	11.812	-0.530
13	3.035	0.436	0.065	0.606	88	****	4.461	1.426	3.129	1.518	2.943	0.128	0.377	0.120	11.844	-0.234
14	4.031	0.871	0.073	0.606	88	****	5.471	1.440	3.799	2.015	3.455	0.170	0.461	0.121	11.855	0.076
15	4.942	1.656	0.096	0.605	88	****	6.375	1.433	4.449	2.471	3.904	0.208	0.536	0.121	11.887	0.362
16	5.807	3.799	0.147	0.604	88	****	7.254	1.447	5.013	2.904	4.351	0.243	0.607	0.121	11.960	0.626
17	6.249	7.825	0.236	0.603	88	****	7.682	1.433	5.362	3.125	4.557	0.258	0.636	0.119	12.088	0.758
18	6.419	13.506	0.332	0.601	89	****	7.838	1.418	5.526	3.210	4.628	0.262	0.641	0.116	12.228	0.803
19	5.959	23.423	0.356	0.601	89	****	7.392	1.433	5.159	2.979	4.412	0.243	0.603	0.117	12.264	0.653
20	5.592	29.540	0.347	0.601	89	****	7.032	1.440	4.884	2.796	4.236	0.228	0.574	0.118	12.251	0.537

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-20-160-16

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.995 IN GS: 2.72 WATER CONTENT: 19.1 %
DIAMETER: 2.870 IN DRY DENSITY: 89.5 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.898 SATURATION: 58 % SUCTION: 15.8 TSF
COMPRESSED TO A VOID RATIO OF 0.567 BY AN ISOTROPIC STRESS OF 11.53 TSF
SUCTION: 0.3 TSF SATURATION: 92 %
REBOUNDED TO A VOID RATIO OF 0.603 BY AN ISOTROPIC STRESS OF 0.74 TSF
SUCTION: 3.9 TSF SATURATION: 86 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.735 IN DIAMETER: 2.520 IN
EQUIVALENT CONSOLIDATION STRESS, Pe: 12.08 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 19.7 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.603	86	3.9	0.785	0.785	1.000	0.	0.785	0.	0.065	0.065	12.063	-1.089
11	0.491	0.017	0.008	0.603	86	4.0	1.268	0.778	1.631	0.245	1.023	0.020	0.105	0.064	12.074	-0.933
12	0.930	0.052	0.017	0.603	86	4.7	1.722	0.792	2.174	0.465	1.257	0.038	0.142	0.066	12.088	-0.799
13	1.490	0.105	0.034	0.603	86	3.2	2.303	0.814	2.831	0.745	1.558	0.061	0.190	0.067	12.112	-0.628
14	1.674	0.174	0.026	0.603	86	3.3	2.423	0.749	3.236	0.837	1.586	0.069	0.200	0.062	12.101	-0.557
15	2.490	0.262	0.046	0.602	86	3.8	3.275	0.785	4.173	1.245	2.030	0.103	0.270	0.065	12.130	-0.309
16	2.941	0.366	0.054	0.602	86	3.1	3.712	0.770	4.818	1.471	2.241	0.121	0.306	0.063	12.142	-0.165
17	3.592	0.506	0.084	0.602	86	3.0	4.391	0.799	5.494	1.796	2.595	0.147	0.360	0.066	12.186	0.031
18	3.977	0.715	0.075	0.602	86	3.0	4.776	0.799	5.976	1.988	2.788	0.163	0.392	0.066	12.171	0.153
19	4.461	0.959	0.061	0.602	86	3.2	5.181	0.720	7.196	2.231	2.951	0.184	0.426	0.059	12.152	0.322
20	5.065	1.290	0.087	0.602	86	3.6	5.835	0.770	7.574	2.532	3.303	0.208	0.479	0.063	12.189	0.500
21	5.372	1.709	0.061	0.602	86	4.5	6.085	0.713	8.536	2.686	3.399	0.221	0.501	0.059	12.151	0.610
22	5.912	2.441	0.079	0.602	86	3.3	6.668	0.756	8.820	2.956	3.712	0.243	0.548	0.062	12.177	0.770
23	6.370	4.725	0.074	0.602	86	2.9	7.155	0.785	9.117	3.185	3.970	0.262	0.588	0.064	12.170	0.910
24	6.737	6.713	0.059	0.602	86	5.2	7.457	0.720	10.357	3.369	4.089	0.277	0.614	0.059	12.149	1.039
25	6.787	9.695	0.063	0.602	86	3.8	7.507	0.720	10.426	3.393	4.113	0.279	0.618	0.059	12.155	1.054
26	6.727	14.298	0.044	0.602	86	3.2	7.454	0.727	10.250	3.363	4.091	0.277	0.615	0.060	12.126	1.036
27	6.772	16.949	0.035	0.603	86	5.9	7.500	0.727	10.313	3.386	4.113	0.280	0.619	0.060	12.114	1.052
28	6.012	25.266	-0.041	0.604	86	3.4	6.746	0.734	9.186	3.006	3.740	0.250	0.562	0.061	12.005	0.819

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-10-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.986 IN GS: 2.72 WATER CONTENT: 27.1 %
DIAMETER: 2.875 IN DRY DENSITY: 94.4 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.798 SATURATION: 93 % SUCTION: 19.6 TSF
COMPRESSED TO A VOID RATIO OF 0.786 BY AN ISOTROPIC STRESS OF 0.76 TSF
SUCTION: 7.4 TSF SATURATION: 94 %
REBOUNDED TO A VOID RATIO OF 0.786 BY AN ISOTROPIC STRESS OF 0.76 TSF
SUCTION: 7.4 TSF SATURATION: 94 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.958 IN DIAMETER: 2.869 IN
EQUIVALENT CONSOLIDATION STRESS, Pe: 3.67 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 27.3 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.786	94	7.4	0.814	0.814	1.000	0.	0.814	0.	0.221	0.221	3.676	-0.438
11	1.001	0.420	0.293	0.780	94	5.4	1.785	0.785	2.275	0.500	1.285	0.132	0.471	0.207	3.788	-0.126
12	1.364	1.208	0.738	0.772	95	1.9	2.178	0.814	2.677	0.682	1.496	0.172	0.549	0.205	3.966	-0.031
13	1.540	3.206	1.232	0.764	97	1.0	2.353	0.814	2.893	0.770	1.583	0.184	0.563	0.195	4.177	0.008
14	1.700	4.985	1.524	0.758	97	0.9	2.442	0.742	3.293	0.850	1.592	0.197	0.567	0.172	4.308	0.061
15	1.804	9.147	1.764	0.754	98	1.0	2.553	0.749	3.409	0.902	1.651	0.204	0.578	0.169	4.419	0.084
16	1.812	17.271	1.784	0.754	98	0.8	2.561	0.749	3.420	0.906	1.655	0.205	0.578	0.169	4.428	0.086
17	1.388	35.683	1.592	0.757	97	0.7	2.136	0.749	2.853	0.694	1.443	0.160	0.492	0.173	4.339	-0.041

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-20-1(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.995 IN GS: 2.72 WATER CONTENT: 26.8 %
DIAMETER: 2.875 IN DRY DENSITY: 94.7 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.793 SATURATION: 92 % SUCTION: 15.5 TSF
COMPRESSED TO A VOID RATIO OF 0.767 BY AN ISOTROPIC STRESS OF 1.45 TSF
SUCTION: 1.5 TSF SATURATION: 95 %
REBOUNDED TO A VOID RATIO OF 0.767 BY AN ISOTROPIC STRESS OF 1.45 TSF
SUCTION: 1.5 TSF SATURATION: 95 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.423 IN DIAMETER: 3.125 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 4.09 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 25.8 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSI q_ψ TSF
10	0.	0.000	0.	0.767	95	1.5	1.404	1.404	1.000	0.	1.404	0.	0.343	0.343	4.096	-0.580
11	0.357	0.129	0.063	0.766	95	2.0	1.789	1.433	1.249	0.178	1.611	0.043	0.434	0.348	4.122	-0.475
12	1.069	0.258	0.170	0.764	95	1.9	2.495	1.426	1.750	0.535	1.960	0.128	0.599	0.342	4.169	-0.253
13	1.704	0.553	0.375	0.760	96	0.4	3.094	1.390	2.226	0.852	2.242	0.200	0.726	0.326	4.259	-0.053
14	1.968	1.070	0.650	0.755	96	1.3	3.358	1.390	2.416	0.984	2.374	0.225	0.766	0.317	4.383	0.020
15	2.050	1.586	0.885	0.751	97	1.1	3.454	1.404	2.460	1.025	2.429	0.228	0.769	0.312	4.493	0.035
16	2.201	3.375	1.294	0.744	98	0.9	3.620	1.418	2.552	1.101	2.519	0.235	0.771	0.302	4.693	0.064
17	2.120	8.335	1.648	0.738	99	0.8	3.532	1.411	2.503	1.060	2.471	0.218	0.725	0.290	4.874	0.026
18	1.817	20.929	1.852	0.734	99	1.7	3.199	1.382	2.314	0.908	2.291	0.182	0.642	0.277	4.983	-0.073

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-20-1(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.979 IN GS: 2.72 WATER CONTENT: 26.1 %
DIAMETER: 2.875 IN DRY DENSITY: 95.1 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.785 SATURATION: 91 % SUCTION: 13.1 TSF
COMPRESSED TO A VOID RATIO OF 0.750 BY AN ISOTROPIC STRESS OF 1.47 TSF
SUCTION: 1.6 TSF SATURATION: 95 %
REBOUNDED TO A VOID RATIO OF 0.750 BY AN ISOTROPIC STRESS OF 1.47 TSF
SUCTION: 1.6 TSF SATURATION: 95 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.920 IN DIAMETER: 2.847 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 4.53 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 25.4 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.750	95	1.6	1.462	1.462	1.000	0.	1.462	0.	0.323	0.323	4.519	-0.624
11	0.407	0.118	0.119	0.748	95	1.3	1.869	1.462	1.279	0.204	1.665	0.045	0.408	0.319	4.576	-0.500
12	1.288	0.456	0.371	0.744	95	1.4	2.749	1.462	1.881	0.644	2.)5	0.137	0.585	0.311	4.700	-0.232
13	1.948	1.486	0.931	0.734	97	1.6	3.409	1.462	2.332	0.974	2.435	0.195	0.683	0.293	4.989	-0.047
14	2.114	3.041	1.444	0.725	98	1.2	3.576	1.462	2.447	1.057	2.519	0.200	0.678	0.277	5.273	-0.017
15	2.293	5.203	1.882	0.717	99	1.3	3.755	1.462	2.569	1.147	2.608	0.207	0.679	0.264	5.531	0.019
16	2.365	7.753	2.208	0.712	100	1.3	3.826	1.462	2.618	1.182	2.644	0.206	0.667	0.255	5.733	0.026
17	2.548	12.753	2.557	0.706	100+	1.0	4.010	1.462	2.744	1.274	2.736	0.214	0.673	0.245	5.960	0.066
18	2.235	23.851	2.691	0.703	100+	1.0	3.697	1.462	2.529	1.118	2.579	0.185	0.611	0.242	6.050	-0.039

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-40-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.976 IN GS: 2.72 WATER CONTENT: 25.4 %
DIAMETER: 2.871 IN DRY DENSITY: 96.3 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.763 SATURATION: 91 % SUCTION: 13.1 TSF
COMPRESSED TO A VOID RATIO OF 0.693 BY AN ISOTROPIC STRESS OF 2.90 TSF
SUCTION: 0.8 TSF SATURATION: 100 %
REBOUNDED TO A VOID RATIO OF 0.693 BY AN ISOTROPIC STRESS OF 2.90 TSF
SUCTION: 0.8 TSF SATURATION: 100 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.872 IN DIAMETER: 2.806 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 6.46 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 23.4 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.693	100	0.8	2.902	2.902	1.000	0.	2.902	0.	0.450	0.450	6.450	-1.041
11	0.792	0.102	0.104	0.691	100	0.7	3.700	2.909	1.272	0.396	3.305	0.061	0.567	0.446	6.525	-0.799
12	1.884	0.324	0.285	0.688	100	0.7	4.786	2.902	1.649	0.942	3.844	0.142	0.719	0.436	6.656	-0.464
13	3.101	0.971	0.673	0.682	100+	1.1	6.002	2.902	2.069	1.550	4.452	0.223	0.864	0.418	6.950	-0.104
14	3.452	1.339	1.082	0.675	100+	1.1	6.354	2.902	2.190	1.726	4.628	0.237	0.873	0.399	7.276	-0.018
15	3.647	2.344	1.444	0.669	100+	1.2	6.556	2.909	2.254	1.824	4.732	0.241	0.865	0.384	7.580	0.018
16	3.779	4.496	1.850	0.662	100+	1.1	6.688	2.909	2.299	1.889	4.798	0.238	0.842	0.366	7.941	0.031
17	3.780	8.089	2.341	0.654	100+	0.7	6.682	2.902	2.303	1.890	4.792	0.225	0.795	0.345	8.406	-0.003
18	4.147	9.394	2.575	0.650	100+	1.0	7.049	2.902	2.429	2.073	4.975	0.240	0.816	0.336	8.639	0.094
19	3.595	19.125	2.900	0.644	100+	1.3	6.496	2.902	2.239	1.797	4.699	0.200	0.724	0.323	8.976	-0.106

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-80-1(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.962 IN GS: 2.72 WATER CONTENT: 27.0 %
DIAMETER: 2.872 IN DRY DENSITY: 95.3 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.782 SATURATION: 94 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.682 BY AN ISOTROPIC STRESS OF 5.76 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.682 BY AN ISOTROPIC STRESS OF 5.76 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.750 IN DIAMETER: 2.810 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 6.94 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 22.9 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.682	100+	****	5.767	5.767	1.000	0.	5.767	0.	0.833	0.833	6.927	-1.609
11	1.299	0.157	0.152	0.680	100+	****	7.073	5.774	1.225	0.650	6.424	0.092	1.004	0.820	7.045	-1.210
12	2.798	0.557	0.391	0.676	100+	****	8.558	5.760	1.486	1.399	7.159	0.193	1.183	0.796	7.236	-0.750
13	4.151	1.287	0.718	0.670	100+	****	9.918	5.767	1.720	2.075	7.843	0.276	1.321	0.768	7.507	-0.346
14	5.128	3.548	1.416	0.659	100+	****	10.880	5.753	1.891	2.564	8.317	0.315	1.339	0.708	8.127	-0.085
15	5.016	5.409	1.768	0.653	100+	****	10.769	5.753	1.872	2.508	8.261	0.296	1.272	0.680	8.465	-0.146
16	5.075	7.896	2.071	0.648	100+	****	10.835	5.760	1.881	2.537	8.297	0.289	1.236	0.657	8.768	-0.153
17	5.124	11.061	2.321	0.643	100+	****	10.891	5.767	1.888	2.562	8.329	0.284	1.206	0.639	9.029	-0.159
18	6.491	13.061	2.759	0.636	100+	****	12.251	5.760	2.127	3.245	9.005	0.341	1.288	0.606	9.510	0.235
19	5.280	16.696	2.901	0.634	100+	****	11.048	5.767	1.916	2.640	8.407	0.273	1.142	0.596	9.672	-0.160

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-80-1(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.981 IN GS: 2.72 WATER CONTENT: 25.7 %
DIAMETER: 2.874 IN DRY DENSITY: 95.9 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.771 SATURATION: 91 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.594 BY AN ISOTROPIC STRESS OF 5.77 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.594 BY AN ISOTROPIC STRESS OF 5.77 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.763 IN DIAMETER: 2.860 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 12.92 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 20.9 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.594	100+	****	5.767	5.767	1.000	0.	5.767	0.	0.447	0.447	12.894	-2.075
11	1.380	0.121	0.226	0.591	100+	****	7.147	5.767	1.239	0.690	6.457	0.052	0.539	0.435	13.252	-1.669
12	3.221	0.347	0.466	0.587	100+	****	8.996	5.774	1.558	1.611	7.385	0.118	0.659	0.423	13.645	-1.121
13	5.045	0.816	0.777	0.582	100+	****	10.805	5.760	1.876	2.523	8.282	0.178	0.762	0.406	14.175	-0.585
14	6.437	1.406	1.114	0.577	100+	****	12.212	5.774	2.115	3.219	8.993	0.218	0.826	0.391	14.779	-0.196
15	6.506	2.256	1.505	0.570	100+	****	12.274	5.767	2.128	3.253	9.020	0.210	0.791	0.372	15.520	-0.231
16	6.688	3.384	1.911	0.564	100+	****	12.469	5.782	2.157	3.344	9.125	0.205	0.763	0.354	16.337	-0.241
17	6.507	5.587	2.383	0.556	100+	****	12.274	5.767	2.128	3.254	9.021	0.187	0.707	0.332	17.355	-0.374
18	6.702	8.572	2.813	0.549	100+	****	12.476	5.774	2.161	3.351	9.125	0.183	0.680	0.315	18.349	-0.392
19	7.814	9.769	3.094	0.545	100+	****	13.588	5.774	2.353	3.907	9.681	0.205	0.714	0.303	19.038	-0.096
20	6.226	17.821	3.416	0.540	100+	****	12.001	5.774	2.078	3.113	8.888	0.157	0.604	0.291	19.866	-0.660
21	5.200	32.362	3.864	0.533	100+	****	10.975	5.774	1.901	2.600	8.375	0.123	0.520	0.274	21.093	-1.080

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-160-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.987 IN GS: 2.72 WATER CONTENT: 26.4 %
DIAMETER: 2.872 IN DRY DENSITY: 95.3 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.781 SATURATION: 92 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.577 BY AN ISOTROPIC STRESS OF 11.58 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.577 BY AN ISOTROPIC STRESS OF 11.58 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.650 IN DIAMETER: 2.691 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 14.73 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 18.9 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.577	100+	****	11.592	11.592	1.000	0.	11.592	0.	0.789	0.789	14.697	-3.294
11	1.948	0.124	0.100	0.576	100+	****	13.504	11.556	1.169	0.974	12.530	0.065	0.908	0.777	14.880	-2.688
12	4.445	0.336	0.238	0.574	100+	****	16.001	11.556	1.385	2.223	13.778	0.147	1.057	0.764	15.134	-1.921
13	7.259	0.796	0.436	0.570	100+	****	18.815	11.556	1.628	3.629	15.185	0.234	1.213	0.745	15.510	-1.064
14	9.226	1.381	0.667	0.567	100+	****	20.782	11.556	1.798	4.613	16.169	0.289	1.302	0.724	15.964	-0.480
15	9.408	2.265	0.944	0.562	100+	****	20.964	11.556	1.814	4.704	16.260	0.285	1.268	0.699	16.531	-0.467
16	9.655	3.558	1.252	0.558	100+	****	21.225	11.570	1.834	4.827	16.398	0.281	1.235	0.673	17.187	-0.443
17	10.160	5.168	1.570	0.552	100+	****	21.730	11.570	1.878	5.080	16.650	0.284	1.214	0.646	17.900	-0.340
18	10.230	7.381	1.864	0.548	100+	****	21.801	11.570	1.884	5.115	16.686	0.275	1.172	0.622	18.594	-0.372
19	10.055	11.027	2.136	0.544	100+	****	21.633	11.578	1.869	5.028	16.605	0.261	1.123	0.601	19.260	-0.481
20	9.064	22.071	2.524	0.537	100+	****	20.628	11.563	1.784	4.532	16.095	0.224	1.018	0.571	20.267	-0.869

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-40-2(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.970 IN GS: 2.72 WATER CONTENT: 26.3 %
DIAMETER: 2.875 IN DRY DENSITY: 95.7 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.775 SATURATION: 92 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.707 BY AN ISOTROPIC STRESS OF 2.89 TSF
SUCTION: 11.0 TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.719 BY AN ISOTROPIC STRESS OF 1.44 TSF
SUCTION: **** TSF SATURATION: 99 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.881 IN DIAMETER: 2.826 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 5.47 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 25.1 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.719	99	****	1.440	1.440	1.000	0.	1.440	0.	0.263	0.263	5.465	-0.694
11	0.848	0.102	0.047	0.718	100	****	2.288	1.440	1.589	0.424	1.864	0.077	0.417	0.262	5.493	-0.429
12	1.757	0.221	0.113	0.717	100	****	3.197	1.440	2.220	0.878	2.318	0.159	0.578	0.260	5.532	-0.146
13	1.865	0.646	0.234	0.715	100	****	3.298	1.433	2.302	0.933	2.365	0.166	0.588	0.256	5.605	-0.116
14	2.175	2.262	0.490	0.711	100+	****	3.615	1.440	2.511	1.088	2.528	0.189	0.627	0.250	5.763	-0.032
15	2.649	4.778	0.762	0.706	100+	****	4.089	1.440	2.839	1.324	2.764	0.223	0.689	0.243	5.936	0.104
16	2.630	10.185	0.935	0.703	100+	****	4.070	1.440	2.827	1.315	2.755	0.217	0.673	0.238	6.050	0.089
17	2.613	15.525	0.948	0.703	100+	****	4.053	1.440	2.815	1.307	2.747	0.216	0.669	0.238	6.058	0.083
18	2.365	23.703	0.910	0.704	100+	****	3.805	1.440	2.642	1.182	2.622	0.196	0.631	0.239	6.033	0.007

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-40-2(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.989 IN GS: 2.72 WATER CONTENT: 26.3 %
DIAMETER: 2.877 IN DRY DENSITY: 95.6 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.775 SATURATION: 92 % SUCTION: 13.8 TSF
COMPRESSED TO A VOID RATIO OF 0.695 BY AN ISOTROPIC STRESS OF 2.89 TSF
SUCTION: 0.5 TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.706 BY AN ISOTROPIC STRESS OF 1.48 TSF
SUCTION: 0.8 TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.829 IN DIAMETER: 2.841 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 5.94 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 25.0 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.706	100+	0.8	1.426	1.426	1.000	0.	1.426	0.	0.241	0.241	5.925	-0.727
11	0.730	0.103	0.024	0.706	100+	1.1	2.149	1.418	1.515	0.365	1.784	0.061	0.362	0.239	5.941	-0.497
12	1.520	0.154	0.068	0.705	100+	0.4	2.967	1.447	2.050	0.760	2.207	0.127	0.497	0.242	5.969	-0.256
13	1.868	0.223	0.107	0.705	100+	1.2	3.323	1.454	2.284	0.934	2.388	0.156	0.554	0.243	5.994	-0.149
14	1.898	0.429	0.178	0.703	100+	1.2	3.367	1.469	2.293	0.949	2.418	0.157	0.557	0.243	6.041	-0.146
15	2.173	1.818	0.405	0.700	100+	0.9	3.649	1.476	2.472	1.087	2.563	0.175	0.589	0.238	6.193	-0.073
16	2.380	4.804	0.627	0.696	100+	0.6	3.799	1.418	2.678	1.190	2.608	0.188	0.599	0.223	6.346	-0.009
17	2.681	6.090	0.756	0.694	100+	1.0	4.128	1.447	2.852	1.340	2.788	0.208	0.641	0.225	6.437	0.073
18	2.630	11.614	0.839	0.692	100+	0.4	4.113	1.483	2.773	1.315	2.798	0.202	0.633	0.228	6.497	0.046
19	2.571	18.185	0.784	0.693	100+	0.9	4.026	1.454	2.768	1.286	2.740	0.199	0.623	0.225	6.457	0.036
20	2.167	30.571	0.793	0.693	100+	0.5	3.614	1.447	2.498	1.084	2.531	0.168	0.559	0.224	6.464	-0.091

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-40-4(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.996 IN GS: 2.72 WATER CONTENT: 25.8 %
DIAMETER: 2.874 IN DRY DENSITY: 95.9 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.771 SATURATION: 91 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.694 BY AN ISOTROPIC STRESS OF 2.88 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.721 BY AN ISOTROPIC STRESS OF 0.72 TSF
SUCTION: **** TSF SATURATION: 97 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.879 IN DIAMETER: 2.848 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 5.41 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 25.9 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.721	97	****	0.713	0.713	1.000	0.	0.713	0.	0.132	0.132	5.405	-0.555
11	0.611	0.119	0.048	0.720	97	****	1.331	0.720	1.849	0.306	1.026	0.056	0.245	0.133	5.433	-0.366
12	1.061	0.204	0.094	0.719	98	****	1.781	0.720	2.473	0.530	1.250	0.097	0.326	0.132	5.460	-0.226
13	1.348	0.425	0.167	0.718	98	****	2.068	0.720	2.873	0.674	1.394	0.122	0.376	0.131	5.503	-0.139
14	1.578	1.412	0.224	0.717	98	****	2.290	0.713	3.213	0.789	1.502	0.142	0.414	0.129	5.537	-0.068
15	1.855	2.262	0.242	0.717	98	****	2.568	0.713	3.602	0.927	1.640	0.167	0.463	0.128	5.548	0.019
16	2.022	5.443	0.210	0.717	98	****	2.735	0.713	3.837	1.011	1.724	0.183	0.495	0.129	5.529	0.073
17	2.095	9.985	0.053	0.720	97	****	2.815	0.720	3.910	1.048	1.768	0.193	0.518	0.132	5.436	0.102
18	1.929	19.374	-0.164	0.724	97	****	2.642	0.713	3.707	0.965	1.677	0.182	0.497	0.134	5.311	0.061
19	1.680	29.716	-0.298	0.726	97	****	2.393	0.713	3.357	0.840	1.553	0.160	0.457	0.136	5.236	-0.012

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-40-4(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.979 IN GS: 2.72 WATER CONTENT: 26.3 %
DIAMETER: 2.875 IN DRY DENSITY: 95.6 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.776 SATURATION: 92 % SUCTION: 12.9 TSF
COMPRESSED TO A VOID RATIO OF 0.705 BY AN ISOTROPIC STRESS OF 2.89 TSF
SUCTION 1.0 TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.736 BY AN ISOTROPIC STRESS OF 0.72 TSF
SUCTION 0.6 TSF SATURATION: 97 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.890 IN DIAMETER: 2.853 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 4.93 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 26.7 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.736	97	0.6	0.720	0.720	1.000	0.	0.720	0.	0.146	0.146	4.920	-0.518
11	0.450	0.085	0.034	0.736	97	0.8	1.192	0.742	1.607	0.225	0.967	0.046	0.241	0.150	4.937	-0.382
12	1.024	0.204	0.092	0.735	97	0.6	1.736	0.713	2.436	0.512	1.225	0.103	0.350	0.143	4.968	-0.198
13	1.362	0.407	0.173	0.733	98	0.5	2.082	0.720	2.891	0.681	1.401	0.136	0.415	0.144	5.011	-0.096
14	1.621	0.951	0.277	0.731	98	1.1	2.370	0.749	3.165	0.811	1.559	0.160	0.468	0.148	5.067	-0.024
15	1.734	1.426	0.343	0.730	98	0.7	2.476	0.742	3.338	0.867	1.609	0.170	0.485	0.145	5.103	0.010
16	1.936	2.649	0.410	0.729	98	0.7	2.685	0.749	3.585	0.968	1.717	0.188	0.522	0.146	5.139	0.069
17	2.061	6.604	0.436	0.729	98	0.5	2.860	0.799	3.579	1.031	1.830	0.200	0.555	0.155	5.154	0.098
18	2 32	9.864	0.309	0.731	98	0.6	2.817	0.734	3.835	1.041	1.776	0.205	0.554	0.144	5.084	0.122
19	1.879	19.457	0.127	0.734	97	0.5	2.628	0.749	3.509	0.939	1.688	0.188	0.527	0.150	4.987	0.063
20	1.589	31.664	-0.010	0.736	97	0.5	2.388	0.799	2.988	0.794	1.594	0.162	0.486	0.163	4.915	-0.032

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-160-2(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.985 IN GS: 2.72 WATER CONTENT: 26.7 %
DIAMETER: 2.874 IN DRY DENSITY: 94.7 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.794 SATURATION: 91 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.580 BY AN ISOTROPIC STRESS OF 11.54 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.594 BY AN ISOTROPIC STRESS OF 5.79 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.688 IN DIAMETER: 2.683 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 12.92 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 20.8 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.594	100+	****	5.789	5.789	1.000	0.	5.789	0.	0.449	0.449	12.903	-2.080
11	1.273	0.018	0.007	0.594	100+	****	7.062	5.789	1.220	0.636	6.425	0.049	0.547	0.448	12.914	-1.680
12	3.002	0.088	0.036	0.594	100+	****	8.797	5.796	1.518	1.501	7.297	0.116	0.679	0.447	12.959	-1.140
13	3.253	0.246	0.059	0.593	100+	****	9.049	5.796	1.561	1.627	7.423	0.125	0.696	0.446	12.996	-1.064
14	4.022	0.563	0.088	0.593	100+	****	9.818	5.796	1.694	2.011	7.807	0.154	0.753	0.444	13.042	-0.825
15	4.922	1.125	0.141	0.592	100+	****	10.726	5.803	1.848	2.461	8.264	0.188	0.817	0.442	13.125	-0.549
16	5.579	2.672	0.242	0.590	100+	****	11.367	5.789	1.964	2.789	8.578	0.210	0.856	0.436	13.287	-0.353
17	6.176	5.204	0.379	0.588	100+	****	11.930	5.803	2.064	3.088	8.891	0.229	0.887	0.430	13.510	-0.185
18	6.692	7.753	0.523	0.586	100+	****	12.495	5.803	2.153	3.346	9.149	0.243	0.909	0.422	13.750	-0.041

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-160-2(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.993 IN GS: 2.72 WATER CONTENT: 26.5 %
DIAMETER: 2.874 IN DRY DENSITY: 95.0 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.788 SATURATION: 91 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.535 BY AN ISOTROPIC STRESS OF 11.54 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0 549 BY AN ISOTROPIC STRESS OF 5.79
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.693 IN DIAMETER: 2.613 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 18.42 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 20.7 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.549	100+	****	5.796	5.796	1.000	0.	5.796	0.	0.315	0.315	18.413	-2.512
11	0.470	0.070	0.001	0.549	100+	****	6.266	5.796	1.081	0.235	6.031	0.013	0.340	0.315	18.410	-2.364
12	2.844	0.123	0.047	0.548	100+	****	8.640	5.796	1.491	1.422	7.218	0.077	0.466	0.313	18.524	-1.625
13	3.964	0.228	0.074	0.548	100+	****	9.760	5.796	1.684	1.982	7.778	0.107	0.525	0.312	18.588	-1.277
14	4.774	0.404	0.113	0.547	100+	****	10.570	5.796	1.824	2.387	8.183	0.128	0.566	0.310	18.680	-1.029
15	5.315	0.826	0.170	0.546	100+	****	11.103	5.789	1.918	2.657	8.446	0.141	0.590	0.308	18.816	-0.868
16	5.899	1.827	0.251	0.545	100+	****	11.681	5.782	2.020	2.950	8.731	0.155	0.614	0.304	19.012	-0.698
17	6.519	3.724	0.348	0.544	100+	****	12.315	5.796	2.125	3.260	9.056	0.169	0.640	0.301	19.249	-0.524
18	7.030	6.728	0.471	0.542	100+	****	12.812	5.782	2.216	3.515	9.297	0.180	0.655	0.296	19.554	-0.384
19	7.317	10.153	0.567	0.540	100+	****	13.098	5.782	2.266	3.658	9.440	0.185	0.662	0.292	19.798	-0.313
20	6.806	18.110	0.657	0.539	100+	****	12.602	5.796	2.174	3.403	9.199	0.170	0.629	0.289	20.030	-0.495
21	5.781	29.844	0.730	0.538	100+	****	11.577	5.796	1.997	2.891	8.687	0.143	0.573	0.287	20.219	-0.832

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-160-4

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.978 IN GS: 2.72 WATER CONTENT: 25.6 %
DIAMETER: 2.874 IN DRY DENSITY: 96.1 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.767 SATURATION: 91 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.575 BY AN ISOTROPIC STRESS OF 11.53 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.605 BY AN ISOTROPIC STRESS OF 2.89 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.743 IN DIAMETER: 2.714 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 11.90 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 22.0 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.605	100+	****	2.902	2.902	1.000	0.	2.902	0.	0.243	0.243	11.930	-1.470
11	0.509	0.052	-0.032	0.605	100+	****	3.411	2.902	1.175	0.254	3.156	0.021	0.287	0.244	11.884	-1.306
12	0.534	0.104	-0.040	0.605	100+	****	3.442	2.909	1.183	0.267	3.176	0.022	0.290	0.245	11.873	-1.298
13	1.031	0.157	-0.049	0.605	100+	****	3.918	2.887	1.357	0.516	3.403	0.043	0.330	0.243	11.861	-1.137
14	1.962	0.244	-0.048	0.605	100+	****	4.864	2.902	1.676	0.981	3.883	0.083	0.410	0.245	11.861	-0.846
15	2.204	0.400	-0.061	0.606	100+	****	5.099	2.894	1.762	1.102	3.996	0.093	0.431	0.244	11.843	-0.767
16	2.798	0.522	-0.064	0.606	100+	****	5.693	2.894	1.967	1.399	4.294	0.118	0.481	0.244	11.839	-0.580
17	3.189	0.818	-0.079	0.606	100+	****	6.083	2.894	2.102	1.594	4.489	0.135	0.515	0.245	11.818	-0.455
18	3.791	1.341	-0.083	0.606	100+	****	6.699	2.909	2.303	1.895	4.804	0.160	0.567	0.246	11.812	-0.268
19	4.411	2.438	-0.088	0.606	100+	****	7.312	2.902	2.520	2.205	5.107	0.187	0.619	0.246	11.805	-0.071
20	4.830	3.744	-0.084	0.606	100+	****	7.718	2.887	2.673	2.415	5.302	0.204	0.653	0.244	11.811	0.064
21	5.058	6.826	-0.102	0.606	100+	****	7.953	2.894	2.748	2.529	5.423	0.215	0.675	0.246	11.786	0.136
22	5.105	10.656	-0.144	0.607	100+	****	8.000	2.894	2.764	2.553	5.447	0.218	0.682	0.247	11.728	0.156
23	4.923	16.699	-0.194	0.608	100+	****	7.832	2.909	2.693	2.462	5.370	0.211	0.672	0.250	11.658	0.101
24	4.576	23.629	-0.169	0.607	100+	****	7.492	2.916	2.569	2.288	5.204	0.196	0.641	0.249	11.693	-0.012

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-160-8

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.972 IN GS: 2.72 WATER CONTENT: 25& %
DIAMETER: 2.876 IN DRY DENSITY: 95.7 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.774 SATURATION: 91 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.568 BY AN ISOTROPIC STRESS OF 11.52 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.623 BY AN ISOTROPIC STRESS OF 1.45 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.758 IN DIAMETER: 2.726 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 10.43 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 23.3 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.623	100+	****	1.433	1.433	1.000	0.	1.433	0.	0.137	0.137	10.457	-1.083
11	0.443	0.035	-0.051	0.623	100+	****	1.898	1.454	1.305	0.222	1.676	0.021	0.183	0.140	10.394	-0.942
12	0.473	0.122	-0.081	0.624	100+	****	1.927	1.454	1.325	0.236	1.691	0.023	0.186	0.140	10.358	-0.930
13	0.880	0.243	-0.120	0.625	100+	****	2.327	1.447	1.608	0.440	1.887	0.043	0.226	0.140	10.310	-0.797
14	1.640	0.399	-0.133	0.625	100+	****	3.080	1.440	2.139	0.820	2.260	0.080	0.299	0.140	10.295	-0.555
15	1.792	0.504	-0.150	0.625	100+	****	3.239	1.447	2.238	0.896	2.343	0.087	0.315	0.141	10.275	-0.507
16	2.171	0.677	-0 167	0.625	100+	****	3.611	1.440	2.507	1.085	2.525	0.106	0.352	0.140	10.254	-0.385
17	2.814	1.320	-0.187	0.626	100+	****	4.254	1.440	2.954	1.407	2.847	0.138	0.416	0.141	10.231	-0.180
18	3.230	2.154	-0.247	0.627	100+	****	4.670	1.440	3.243	1.615	3.055	0.159	0.460	0.142	10.159	-0.043
19	3.708	4.029	-0.346	0.628	100+	****	5.169	1.462	3.537	1.854	3.316	0.185	0.515	0.146	10.043	0.112
20	3.925	8.024	-0.509	0.631	100+	****	5.372	1.447	3.712	1.963	3.410	0.199	0.545	0.147	9.854	0.198
21	3.838	14.172	-0.704	0.634	100+	****	5.278	1.440	3.665	1.919	3.359	0.199	0.548	0.149	9.636	0.189
22	3.370	24.505	-0.934	0.638	100+	****	4.803	1.433	3.352	1.685	3.118	0.180	0.512	0.153	9.385	0.063

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-0-DR-26-160-16

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.984 IN GS: 2.72 WATER CONTENT: 26.3 %
DIAMETER: 2.873 IN DRY DENSITY: 96.0 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.788 SATURATION: 91 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.576 BY AN ISOTROPIC STRESS OF 11.54 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.664 BY AN ISOTROPIC STRESS OF 0.73 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.790 IN DIAMETER: 2.762 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 7.83 TSF

SOLUTE SUCTION: 0. TSF

POST-TEST WATER CONTENT: 24.3 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.664	100+	****	0.734	0.734	1.000	0.	0.734	0.	0.094	0.094	7.823	-0.748
11	0.120	0.017	-0.021	0.664	100+	****	0.833	0.713	1.169	0.060	0.773	0.008	0.107	0.091	7.804	-0.704
12	0.587	0.069	-0.006	0.664	100+	****	1.329	0.742	1.792	0.294	1.035	0.038	0.170	0.095	7.818	-0.564
13	0.758	0.121	0.003	0.664	100+	****	1.499	0.742	2.022	0.379	1.120	0.048	0.192	0.095	7.826	-0.511
14	1.037	0.242	0.028	0.664	100+	****	1.750	0.713	2.455	0.518	1.231	0.066	0.223	0.091	7.849	-0.419
15	1.440	0.397	0.062	0.663	100+	****	2.189	0.749	2.923	0.720	1.469	0.091	0.278	0.095	7.878	-0.301
16	1.469	0.501	0.070	0.663	100+	****	2.182	0.713	3.061	0.734	1.447	0.093	0.277	0.090	7.885	-0.286
17	1.808	0.984	0.087	0.663	100+	****	2.536	0.727	3.487	0.904	1.631	0.114	0.321	0.092	7.900	-0.183
18	2.113	1.313	0.093	0.663	100+	****	2.847	0.734	3.877	1.056	1.791	0.134	0.360	0.093	7.906	-0.089
19	2.397	2.694	0.021	0.664	100+	****	3.117	0.720	4.330	1.199	1.919	0.153	0.398	0.092	7.842	0.009
20	2.694	4.387	-0.109	0.666	100+	****	3.422	0.727	4.705	1.347	2.074	0.174	0.443	0.094	7.728	0.110
21	2.803	7.271	-0.382	0.670	100+	****	3.545	0.742	4.780	1.401	2.143	0.187	0.473	0.099	7.496	0.160
22	2.751	14.542	-0.775	0.677	100+	****	3.499	0.749	4.673	1.375	2.124	0.192	0.488	0.104	7.175	0.167

APPENDIX VII

TRIAXIAL COMPRESSION TESTS ON UNSATURATED SPECIMENS TREATED WITH POTASSIUM CHLORIDE

APPENDIX VII. TRIAXIAL COMPRESSION TESTS ON UNSATURATED SPECIMENS TREATED WITH POTASSIUM CHLORIDE

Five specimens which were compacted dry of optimum and eight specimens which were compacted wet of optimum were tested as natural water content specimens. Results from these tests were referred to as "unsaturated" throughout the text although pore water may have drained from some specimens which were consolidated to high degrees of saturation by large applied stresses. Each specimen was treated with a sufficient quantity, by weight, of potassium chloride (KCl) prior to compaction to produce an estimated solute suction of 25 tsf (2.4 MPa).

Each specimen was identified using the nomenclature described below. For example, the identification code for specimen number TXS-25-DR-20-10-1(2) was:

TXS - Triaxial shear test

25 - Estimated value of solute suction, tsf, based upon the weight of KCl added to the pore water

DR - Specimen was tested at its natural water content

20 - Nominal water content of the test specimen, percent

10 - Applied isotropic stress used to consolidate the test specimen, psi (1 psi = 0.07 tsf = 6.9 kPa)

1 - Numerical value analogous to an overconsolidation ratio. For a value of 1, the specimen was sheared at the consolidation stress; for a value of 2, the specimen was rebounded to 1/2 of the consolidation stress prior to shear; for a value of 4, the specimen was rebounded to 1/4 of the consolidation stress prior to shear; etc.

(2) - Number of the test specimen which was subjected to that particular consolidation and rebound sequence prior to shear. (1) - first specimen, (2) - second specimen, etc.

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-20-10-1(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.998 IN GS: 2.72 WATER CONTENT: 19.2 %
DIAMETER: 2.871 IN DRY DENSITY: 90.9 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.868 SATURATION: 60 % SUCTION: 33.9 TSF
COMPRESSED TO A VOID RATIO OF 0.856 BY AN ISOTROPIC STRESS OF 0.78 TSF
SUCTION: 33.3 TSF SATURATION: 61 %
REBOUNDED TO A VOID RATIO OF 0.856 BY AN ISOTROPIC STRESS OF 0.78 TSF
SUCTION: 33.3 TSF SATURATION: 61 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.993 IN DIAMETER: 2.855 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 2.50 TSF

SOLUTE SUCTION: 25.2 TSF

POST-TEST WATER CONTENT: 19.9 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.006	0.	0.856	61	33.3	0.763	0.763	1.000	0.	0.763	0.	0.306	0.306	2.493	-0.336
11	0.754	0.184	0.084	0.855	61	33.9	1.546	0.792	1.951	0.377	1.169	0.150	0.615	0.315	2.514	-0.106
12	1.803	0.517	0.396	0.849	62	33.6	2.602	0.799	3.256	0.901	1.700	0.348	1.004	0.308	2.592	0.217
13	2.224	1.035	0.791	0.842	62	32.7	3.037	0.814	3.733	1.112	1.925	0.413	1.127	0.302	2.695	0.339
14	2.498	1.568	1.177	0.835	63	32.4	3.283	0.785	4.184	1.249	2.034	0.446	1.172	0.280	2.801	0.423
15	2.845	2.670	1.897	0.821	64	32.4	3.673	0.828	4.436	1.422	2.250	0.472	1.220	0.275	3.012	0.507
16	3.173	4.772	3.078	0.799	65	31.9	3.986	0.814	4.900	1.586	2.400	0.466	1.172	0.239	3.401	0.583
17	3.468	7.058	4.233	0.778	67	31.3	4.267	0.799	5.339	1.734	2.533	0.451	1.110	0.208	3.844	0.644
18	3.681	9.328	5.186	0.760	69	31.2	4.523	0.842	5.369	1.840	2.683	0.432	1.061	0.198	4.263	0.670
19	3.856	11.764	6.117	0.743	70	30.9	4.640	0.785	5.913	1.928	2.713	0.408	0.982	0.166	4.728	0.700
20	4.045	14.717	7.155	0.724	72	30.5	4.816	0.770	6.251	2.023	2.793	0.380	0.905	0.145	5.320	0.716
21	4.258	17.053	7.883	0.710	74	30.6	5.050	0.792	6.377	2.129	2.921	0.368	0.872	0.137	5.791	0.742
22	4.361	19.256	8.487	0.699	75	30.6	5.182	0.821	6.313	2.180	3.001	0.350	0.833	0.132	6.221	0.735
23	4.449	21.692	9.063	0.688	76	30.5	5.256	0.806	6.518	2.225	3.031	0.334	0.788	0.121	6.668	0.731
24	4.523	23.578	9.438	0.681	77	31.1	5.279	0.756	6.983	2.262	3.018	0.324	0.756	0.108	6.980	0.739
25	4.400	30.102	10.344	0.664	79	30.5	5.206	0.806	6.456	2.200	3.006	0.282	0.667	0.103	7.811	0.626

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-20-20-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.996 IN GS: 2.72 WATER CONTENT: 19.6 %
DIAMETER: 2.871 IN DRY DENSITY: 92.1 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.843 SATURATION: 63 % SUCTION: 32.7 TSF
COMPRESSED TO A VOID RATIO OF 0.823 BY AN ISOTROPIC STRESS OF 1.46 TSF
SUCTION: 32.5 TSF SATURATION: 65 %
REBOUNDED TO A VOID RATIO OF 0.823 BY AN ISOTROPIC STRESS OF 1.46 TSF
SUCTION: 32.5 TSF SATURATION: 65 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.979 IN DIAMETER: 2.849 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 2.98 TSF

SOLUTE SUCTION: 24.2 TSF

POST-TEST WATER CONTENT: 20.5 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.823	65	32.5	1.534	1.534	1.000	0.	1.534	0.	0.515	0.515	2.979	-0.517
11	1.083	0.251	0.188	0.820	65	32.1	2.588	1.505	1.720	0.542	2.046	0.178	0.853	0.496	3.035	-0.175
12	2.615	1.271	1.158	0.802	66	31.9	4.142	1.526	2.713	1.308	2.834	0.391	1.237	0.456	3.348	0.280
13	3.323	3.044	2.682	0.774	69	31.4	4.893	1.570	3.117	1.661	3.231	0.423	1.247	0.400	3.923	0.450
14	3.694	5.787	4.516	0.741	72	31.4	5.271	1.577	3.343	1.847	3.424	0.386	1.102	0.330	4.785	0.498
15	4.003	9.232	6.299	0.708	75	30.9	5.507	1.505	3.660	2.001	3.506	0.342	0.941	0.257	5.855	0.525
16	4.359	12.477	7.642	0.684	78	31.1	5.857	1.498	3.911	2.179	3.677	0.318	0.854	0.218	6.859	0.560
17	4.678	15.638	8.765	0.663	80	30.8	6.255	1.577	3.967	2.339	3.916	0.297	0.795	0.201	7.863	0.567
18	4.862	19.267	9.776	0.645	83	30.7	6.460	1.598	4.042	2.431	4.029	0.272	0.724	0.179	8.926	[illegible]
19	4.986	22.663	10.512	0.632	84	30.6	6.563	1.577	4.162	2.493	4.070	0.254	0.669	0.161	9.811	0.512
20	5.020	26.627	11.171	0.620	86	30.5	6.554	1.534	4.274	2.510	4.044	0.235	0.613	0.143	10.697	0.461
21	4.864	31.510	11.700	0.610	87	30.3	6.369	1.505	4.232	2.432	3.937	0.212	0.555	0.131	11.479	0.356
22	4.923	34.019	11.890	0.606	88	30.3	6.435	1.512	4.256	2.461	3.973	0.209	0.546	0.128	11.775	0.350

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-20-40-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 6.001 IN GS: 2.72 WATER CONTENT: 19.2 %
DIAMETER: 2.871 IN DRY DENSITY: 89.8 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.890 SATURATION: 59 % SUCTION: 30.4 TSF
COMPRESSED TO A VOID RATIO OF 0.750 BY AN ISOTROPIC STRESS OF 2.87 TSF
SUCTION: 30.0 TSF SATURATION: 70 %
REBOUNDED TO A VOID RATIO OF 0.750 BY AN ISOTROPIC STRESS OF 2.87 TSF
SUCTION: 30.0 TSF SATURATION: 70 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.886 IN DIAMETER: 2.707 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 4.53 TSF

SOLUTE SUCTION: 25.2 TSF

POST-TEST WATER CONTENT: 20.3 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.750	70	30.0	2.866	2.866	1.000	0.	2.866	0.	0.634	0.634	4.521	-0.884
11	0.926	0.068	0.076	0.749	70	30.7	3.777	2.851	1.325	0.463	3.314	0.102	0.829	0.626	4.557	-0.592
12	2.698	1.002	0.932	0.734	71	31.8	5.564	2.866	1.942	1.349	4.215	0.270	1.115	0.574	4.990	-0.070
13	4.587	3.585	2.968	0.698	75	32.0	7.445	2.858	2.605	2.293	5.152	0.367	1.193	0.458	6.243	0.428
14	4.842	6.796	4.832	0.666	78	32.0	7.693	2.851	2.698	2.421	5.272	0.313	0.994	0.368	7.741	0.392
15	5.260	9.395	5.998	0.645	81	31.2	8.118	2.858	2.840	2.630	5.488	0.295	0.912	0.321	8.904	0.432
16	5.606	12.963	7.180	0.625	84	31.2	8.478	2.873	2.951	2.803	5.676	0.272	0.822	0.279	10.310	0.428
17	5.756	16.123	7.898	0.612	85	30.7	8.615	2.858	3.014	2.878	5.737	0.255	0.763	0.253	11.296	0.401
18	5.772	19.776	8.421	0.603	87	30.6	8.623	2.851	3.024	2.886	5.737	0.239	0.713	0.236	12.089	0.345
19	5.869	22.222	8.657	0.599	87	30.8	8.727	2.858	3.053	2.934	5.793	0.235	0.700	0.229	12.468	0.345
20	5.553	28.270	8.970	0.593	88	30.9	8.411	2.858	2.943	2.776	5.635	0.214	0.647	0.220	12.995	0.204
21	5.345	32.739	9.093	0.591	88	31.2	8.204	2.858	2.870	2.673	5.531	0.202	0.621	0.216	13.209	0.122

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-20-80-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.995 IN GS: 2.72 WATER CONTENT: 19.0 %
DIAMETER: 2.870 IN DRY DENSITY: 87.6 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.938 SATURATION: 55 % SUCTION: 31.7 TSF
COMPRESSED TO A VOID RATIO OF 0.653 BY AN ISOTROPIC STRESS OF 5.76 TSF
SUCTION: 31.9 TSF SATURATION: 79 %
REBOUNDED TO A VOID RATIO OF 0.653 BY AN ISOTROPIC STRESS OF 5.76 TSF
SUCTION: 31.9 TSF SATURATION: 79 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.782 IN DIAMETER: 2.524 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 8.44 TSF

SOLUTE SUCTION: 25.4 TSF

POST-TEST WATER CONTENT: 19.7 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.653	79	31.9	5.760	5.760	1.000	0.	5.760	0.	0.683	0.683	8.429	-1.725
11	1.604	0.225	0.068	0.652	79	31.7	7.371	5.767	1.278	0.802	6.569	0.094	0.868	0.679	8.495	-1.226
12	4.002	0.882	0.637	0.643	80	31.8	9.754	5.753	1.696	2.001	7.754	0.221	1.076	0.634	9.069	-0.513
13	6.348	2.508	1.882	0.622	83	31.7	12.101	5.753	2.104	3.174	8.927	0.302	1.153	0.548	10.498	0.114
14	7.822	3.753	2.668	0.609	85	31.4	13.574	5.753	2.360	3.911	9.664	0.339	1.176	0.498	11.543	0.497
15	7.908	4.946	3.253	0.599	86	31.5	13.653	5.746	2.376	3.954	9.699	0.319	1.101	0.463	12.405	0.458
16	8.212	6.745	3.917	0.588	88	31.2	13.964	5.753	2.427	4.106	9.859	0.305	1.036	0.427	13.480	0.468
17	8.357	8.526	4.377	0.581	89	32.3	14.109	5.753	2.453	4.178	9.931	0.292	0.987	0.403	14.292	0.450
18	8.594	10.550	4.735	0.575	90	32.1	14.347	5.753	2.494	4.297	10.050	0.287	0.959	0.384	14.967	0.473
19	8.936	12.543	5.030	0.570	91	30.9	14.696	5.760	2.551	4.468	10.228	0.287	0.945	0.370	15.550	0.533
20	9.240	14.476	5.222	0.567	91	30.2	15.008	5.767	2.602	4.620	10.387	0.290	0.941	0.362	15.946	0.597
21	9.037	18.160	5.430	0.563	92	29.3	14.804	5.767	2.567	4.518	10.285	0.276	0.903	0.352	16.389	0.498
22	8.557	23.521	5.572	0.561	92	28.8	14.324	5.767	2.484	4.279	10.046	0.256	0.858	0.345	16.699	0.323

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-20-160-1

AS COMPACTED SPECIMEN CHARACTERISTICS·
HEIGHT: 5.996 IN GS: 2.72 WATER CONTENT: 19.7 %
DIAMETER: 2.870 IN DRY DENSITY: 91.9 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.849 SATURATION: 63 % SUCTION: 32.2 TSF
COMPRESSED TO A VOID RATIO OF 0.560 BY AN ISOTROPIC STRESS OF 11.58 TSF
SUCTION: 22.3 TSF SATURATION: 96 %
REBOUNDED TO A VOID RATIO OF 0.560 BY AN ISOTROPIC STRESS OF 11.58 TSF
SUCTION: 22.3 TSF SATURATION: 96 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.715 IN DIAMETER: 2.527 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 16.85 TSF

SOLUTE SUCTION: 24.5 TSF

POST-TEST WATER CONTENT: 17.7 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.560	96	22.3	11.563	11.563	1.000	0.	11.563	0.	0.687	0.687	16.839	-3.456
11	2.295	0.122	0.111	0.558	96	24.8	13.873	11.578	1.198	1.148	12.725	0.067	0.812	0.678	17.074	-2.754
12	5.500	0.350	0.268	0.556	96	25.1	17.070	11.570	1.475	2.750	14.320	0.158	0.980	0.664	17.415	-1.770
13	8.222	0.787	0.549	0.551	97	25.8	19.799	11.578	1.710	4.111	15.688	0.228	1.097	0.642	18.046	-0.963
14	10.992	1.330	0.863	0.547	98	25.7	22.577	11.585	1.949	5.496	17.081	0.293	1.202	0.617	18.786	-0.150
15	12.570	2.030	1.209	0.541	99	25.8	24.162	11.592	2.084	6.285	17.877	0.320	1.230	0.590	19.642	0.279
16	13.147	2.852	1.563	0.536	100	26.0	24.710	11.563	2.137	6.574	18.137	0.320	1.201	0.562	20.572	0.394
17	13.482	4.129	1.998	0.529	100+	26.3	25.045	11.563	2.166	6.741	18.304	0.309	1.150	0.531	21.784	0.404
18	13.959	5.197	2.277	0.525	100+	26.1	25.522	11.563	2.207	6.980	18.543	0.309	1.129	0.511	22.609	0.490
19	14.310	6.509	2.555	0.520	100+	26.0	25.880	11.570	2.237	7.155	18.725	0.305	1.103	0.493	23.471	0.532
20	14.563	8.259	2.823	0.516	100+	26.1	26.140	11.578	2.258	7.281	18.859	0.299	1.074	0.476	24.338	0.542
21	15.322	9.641	3.012	0.513	100+	26.1	26.906	11.585	2.323	7.661	19.246	0.307	1.077	0.464	24.974	0.730
22	14.975	12.353	3.209	0.510	100+	26.3	26.567	11.592	2.292	7.488	19.080	0.292	1.036	0.452	25.556	0.566
23	15.264	14.471	3.334	0.508	100+	26.1	26.820	11.556	2.321	7.632	19.188	0.292	1.027	0.443	26.103	0.629
24	14.851	18.040	3.457	0.506	100+	26.2	25.399	11.549	2.286	7.425	18.974	0.280	0.994	0.435	26.552	0.465
25	14.653	21.050	3.518	0.505	100+	26.0	26.217	11.563	2.267	7.327	18.890	0.274	0.979	0.432	26.777	0.383

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-26-10-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.983 IN GS: 2.72 WATER CONTENT: 25.6 %
DIAMETER: 2.871 IN DRY DENSITY: 95.8 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.772 SATURATION: 90 % SUCTION: 33.4 TSF
COMPRESSED TO A VOID RATIO OF 0.767 BY AN ISOTROPIC STRESS OF 0.72 TSF
SUCTION: 29.1 TSF SATURATION: 91 %
REBOUNDED TO A VOID RATIO OF 0.767 BY AN ISOTROPIC STRESS OF 0.72 TSF
SUCTION: 29.1 TSF SATURATION: 91 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.972 IN DIAMETER: 2.868 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 4.09 TSF

SOLUTE SUCTION: 24.8 TSF

POST-TEST WATER CONTENT: 26.2 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.767	91	29.1	0.720	0.720	1.000	0.	0.720	0.	0.176	0.176	4.082	-0.452
11	0.468	0.100	0.113	0.765	91	29.2	1.188	0.720	1.650	0.234	0.954	0.057	0.288	0.174	4.130	-0.309
12	1.250	0.352	0.320	0.762	91	29.1	1.970	0.720	2.736	0.625	1.345	0.148	0.467	0.171	4.220	-0.070
13	1.358	0.536	0.450	0.760	92	29.1	2.071	0.713	2.906	0.679	1.392	0.159	0.484	0.167	4.278	-0.039
14	1.709	1.005	0.733	0.755	92	28.8	2.429	0.720	3.373	0.854	1.574	0.194	0.551	0.163	4.407	0.060
15	1.830	1.942	1.065	0.749	93	28.4	2.550	0.720	3.542	0.915	1.635	0.200	0.559	0.158	4.565	0.086
16	2.085	2.780	1.278	0.745	93	28.2	2.805	0.720	3.895	1.042	1.762	0.223	0.601	0.154	4.670	0.158
17	2.136	5.710	1.562	0.740	94	28.2	2.856	0.720	3.967	1.068	1.788	0.222	0.593	0.150	4.814	0.163
18	2.222	8.038	1.699	0.737	94	28.2	2.942	0.720	4.086	1.111	1.831	0.227	0.602	0.147	4.885	0.185
19	2.266	10.432	1.773	0.736	95	28.7	2.986	0.720	4.147	1.133	1.853	0.230	0.606	0.146	4.924	0.195
20	2.204	14.434	1.845	0.735	95	28.7	2.924	0.720	4.062	1.102	1.822	0.222	0.589	0.145	4.963	0.173
21	1.879	26.524	1.867	0.734	95	29.1	2.591	0.713	3.636	0.939	1.652	0.189	0.521	0.143	4.975	0.071
22	1.735	35.934	1.845	0.735	95	29.6	2.455	0.720	3.409	0.867	1.587	0.175	0.495	0.145	4.963	0.025

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-26-20-1(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.991 IN GS: 2.72 WATER CONTENT: 26.2 %
DIAMETER: 2.875 IN DRY DENSITY: 95.5 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.779 SATURATION: 92 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.746 BY AN ISOTROPIC STRESS OF 1.43 TSF
SUCTION: **** TSF SATURATION: 96 %
REBOUNDED TO A VOID RATIO OF 0.746 BY AN ISOTROPIC STRESS OF 1.43 TSF
SUCTION: **** TSF SATURATION: 96 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.936 IN DIAMETER: 2.848 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 4.64 TSF

SOLUTE SUCTION: 24.2 TSF

POST-TEST WATER CONTENT: 24.9 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.746	95	****	1.433	1.433	1.000	0.	1.433	0.	0.310	0.310	4.628	-0.627
11	0.271	0.034	0.075	0.745	96	****	1.697	1.426	1.190	0.136	1.561	0.029	0.364	0.306	4.665	-0.543
12	1.243	0.219	0.239	0.742	96	****	2.669	1.426	1.872	0.622	2.047	0.131	0.562	0.300	4.747	-0.243
13	2.359	0.691	0.623	0.735	97	****	3.784	1.426	2.654	1.179	2.605	0.238	0.765	0.288	4.945	0.093
14	2.564	1.432	1.116	0.727	98	****	3.990	1.426	2.799	1.282	2.708	0.246	0.765	0.273	5.213	0.136
15	2.728	2.038	1.460	0.721	99	****	4.154	1.426	2.914	1.364	2.790	0.252	0.768	0.263	5.411	0.172
16	2.894	3.184	1.918	0.713	100	****	4.319	1.426	3.030	1.447	2.872	0.254	0.759	0.251	5.690	0.203
17	3.111	3.892	2.202	0.708	100+	****	4.529	1.418	3.193	1.555	2.974	0.265	0.771	0.242	5.872	0.258
18	3.303	5.222	2.534	0.702	100+	****	4.721	1.418	3.329	1.651	3.070	0.271	0.775	0.233	6.093	0.302
19	3.331	8.019	2.927	0.695	100+	****	4.771	1.440	3.313	1.665	3.105	0.262	0.749	0.226	6.368	0.285
20	3.229	13.848	3.221	0.690	100+	****	4.669	1.440	3.242	1.614	3.054	0.245	0.709	0.219	6.584	0.236
21	3.225	18.261	3.351	0.688	100+	****	4.665	1.440	3.240	1.613	3.053	0.241	0.698	0.215	6.682	0.227
22	2.601	31.334	3.326	0.688	100+	****	4.041	1.440	2.806	1.301	2.741	0.195	0.606	0.216	6.663	0.032
23	2.530	35.731	3.310	0.689	100+	****	3.970	1.440	2.757	1.265	2.705	0.190	0.597	0.217	6.651	0.011

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-26-20-1(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.996 IN GS: 2.72 WATER CONTENT: 26.0 %
DIAMETER: 2.875 IN DRY DENSITY: 96.3 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.764 SATURATION: 93 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.731 BY AN ISOTROPIC STRESS OF 1.45 TSF
SUCTION: 25.5 TSF SATURATION: 97 %
REBOUNDED TO A VOID RATIO OF 0.731 BY AN ISOTROPIC STRESS OF 1.45 TSF
SUCTION: 25.5 TSF SATURATION: 97 %

PRE-SHEAR CONDITIONS:
HEIGHT: 5.904 IN DIAMETER: 2.865 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 5.08 TSF

SOLUTE SUCTION: 24.5 TSF

POST-TEST WATER CONTENT: 24.6 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.731	97	25.5	1.462	1.462	1.000	0.	1.462	0.	0.288	0.288	5.083	-0.668
11	0.825	0.186	0.124	0.729	97	25.8	2.272	1.447	1.570	0.413	1.860	0.080	0.441	0.281	5.150	-0.411
12	2.024	0.694	0.497	0.722	98	25.2	3.471	1.447	2.398	1.012	2.459	0.189	0.647	0.270	5.361	-0.049
13	2.313	2.033	1.110	0.712	99	25.0	3.775	1.462	2.583	1.157	2.618	0.202	0.659	0.255	5.730	0.010
14	2.584	3.709	1.597	0.703	100+	25.0	4.045	1.462	2.768	1.292	2.753	0.214	0.669	0.242	6.045	0.071
15	2.747	5.877	2.006	0.696	100+	25.2	4.194	1.447	2.898	1.373	2.821	0.217	0.663	0.229	6.326	0.103
16	2.900	9.214	2.272	0.692	100+	24.8	4.362	1.462	2.984	1.450	2.912	0.222	0.669	0.224	6.518	0.133
17	3.306	10.383	2.385	0.690	100+	25.6	4.761	1.454	3.273	1.653	3.108	0.250	0.721	0.220	6.602	0.256
18	2.954	19.936	2.444	0.689	100+	25.1	4.415	1.462	3.021	1.477	2.938	0.222	0.664	0.220	6.645	0.140
19	2.588	30.657	2.382	0.690	100+	25.2	4.064	1.476	2.753	1.294	2.770	0.196	0.616	0.224	6.599	0.026

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-26-40-1(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.985 IN GS: 2.72 WATER CONTENT: 26.1 %
DIAMETER: 2.874 IN DRY DENSITY: 95.2 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.783 SATURATION: 91 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.704 BY AN ISOTROPIC STRESS OF 2.89 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.704 BY AN ISOTROPIC STRESS OF 2.89 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.880 IN DIAMETER: 2.795 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 6.02 TSF

SOLUTE SUCTION: 24.4 TSF

POST-TEST WATER CONTENT: 21.1 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.704	100+	****	2.894	2.894	1.000	0.	2.894	0.	0.480	0.480	6.036	-1.007
11	0.751	0.153	0.092	0.702	100+	****	3.645	2.894	1.259	0.375	3.270	0.062	0.598	0.475	6.097	-0.776
12	1.641	0.289	0.217	0.700	100+	****	4.529	2.887	1.569	0.821	3.708	0.133	0.733	0.467	6.180	-0.500
13	2.921	0.867	0.632	0.693	100+	****	5.801	2.880	2.014	1.461	4.341	0.226	0.897	0.445	6.470	-0.118
14	3.747	1.820	1.166	0.684	100+	****	6.627	2.880	2.301	1.874	4.754	0.273	0.965	0.419	6.866	0.111
15	4.284	2.874	1.667	0.675	100+	****	7.178	2.894	2.480	2.142	5.036	0.295	0.988	0.398	7.265	0.246
16	4.537	4.456	2.234	0.665	100+	****	7.439	2.902	2.564	2.268	5.170	0.293	0.960	0.374	7.751	0.286
17	4.621	7.211	2.843	0.655	100+	****	7.508	2.887	2.600	2.310	5.198	0.278	0.903	0.347	8.318	0.271
18	4.668	13.078	3.392	0.646	100+	****	7.562	2.894	2.613	2.334	5.228	0.263	0.852	0.326	8.875	0.241
19	4.542	22.228	3.894	0.637	100+	****	7.437	2.894	2.569	2.271	5.165	0.241	0.789	0.307	9.423	0.158
20	3.804	33.503	3.980	0.636	100+	****	6.698	2.894	2.314	1.902	4.796	0.200	0.704	0.304	9.521	-0.082
21	3.093	36.241	3.935	0.637	100+	****	5.994	2.902	2.066	1.546	4.448	0.163	0.633	0.306	9.469	-0.303

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-26-40-1(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.997 IN GS: 2.72 WATER CONTENT: 26.0 %
DIAMETER: 2.872 IN DRY DENSITY: 96.7 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.755 SATURATION: 94 % SUCTION: 32.0 TSF
COMPRESSED TO A VOID RATIO OF 0.685 BY AN ISOTROPIC STRESS OF 2.89 TSF
SUCTION: 25.9 TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.685 BY AN ISOTROPIC STRESS OF 2.89 TSF
SUCTION: 25.9 TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.850 IN DIAMETER: 2.826 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 6.81 TSF

SOLUTE SUCTION: 24.5 TSF

POST-TEST WATER CONTENT: 23.1 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.685	100+	25.9	2.887	2.887	1.000	0.	2.887	0.	0.426	0.426	6.785	-1.065
11	0.643	0.120	0.110	0.684	100+	26.1	3.559	2.916	1.220	0.321	3.237	0.047	0.518	0.425	6.868	-0.874
12	1.880	0.325	0.282	0.681	100+	25.5	4.775	2.894	1.650	0.940	3.835	0.134	0.682	0.413	7.000	-0.491
13	3.268	0.855	0.646	0.675	100+	25.6	6.184	2.916	2.121	1.634	4.550	0.224	0.848	0.400	7.291	-0.080
14	3.452	2.120	1.213	0.665	100+	25.7	6.354	2.902	2.190	1.726	4.628	0.222	0.817	0.373	7.775	-0.057
15	4.648	2.991	1.696	0.657	100+	25.5	7.550	2.902	2.602	2.324	5.226	0.283	0.919	0.353	8.218	0.285
16	4.536	4.000	2.054	0.651	100+	25.5	7.445	2.909	2.560	2.268	5.177	0.265	0.869	0.340	8.565	0.221
17	4.261	6.188	2.442	0.644	100+	25.4	7.155	2.894	2.472	2.130	5.025	0.238	0.798	0.323	8.964	0.106
18	4.942	9.812	2.947	0.636	100+	25.5	7.844	2.902	2.703	2.471	5.373	0.260	0.824	0.305	9.516	0.276
19	4.802	15.128	3.163	0.632	100+	25.4	7.711	2.909	2.651	2.401	5.310	0.246	0.790	0.298	9.765	0.211
20	4.299	24.274	3.278	0.630	100+	25.2	7.201	2.902	2.482	2.150	5.051	0.217	0.727	0.293	9.901	0.043
21	4.160	28.684	3.290	0.630	100+	25.1	7.061	2.902	2.434	2.080	4.981	0.210	0.712	0.293	9.916	-0.002
22	3.752	35.179	3.301	0.630	100+	24.8	6.647	2.894	2.296	1.876	4.770	0.189	0.669	0.292	9.928	-0.130

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-26-80-1

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.983 IN GS: 2.72 WATER CONTENT: 25.5 %
DIAMETER: 2.875 IN DRY DENSITY: 95.5 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.778 SATURATION: 89 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.622 BY AN ISOTROPIC STRESS OF 5.76 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.622 BY AN ISOTROPIC STRESS OF 5.76 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.782 IN DIAMETER: 2.711 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 10.51 TSF

SOLUTE SUCTION: 24.9 TSF

POST-TEST WATER CONTENT: 20.4 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.622	100+	****	5.753	5.753	1.000	0.	5.753	0.	0.547	0.547	10.522	-1.887
11	0.250	0.052	0.051	0.621	100+	****	6.017	5.767	1.043	0.125	5.892	0.012	0.568	0.545	10.585	-1.816
12	1.222	0.138	0.117	0.620	100+	****	6.982	5.760	1.212	0.611	6.371	0.057	0.655	0.540	10.667	-1.515
13	2.567	0.311	0.247	0.618	100+	****	8.320	5.753	1.446	1.283	7.036	0.118	0.768	0.531	10.833	-1.103
14	4.053	0.623	0.453	0.614	100+	****	9.820	5.767	1.703	2.027	7.794	0.183	0.885	0.520	11.100	-0.658
15	5.820	1.124	0.762	0.609	100+	****	11.587	5.767	2.009	2.910	8.677	0.253	1.006	0.501	11.516	-0.134
16	6.812	1.730	1.096	0.604	100+	****	12.579	5.767	2.181	3.406	9.173	0.284	1.049	0.481	11.988	0.142
17	6.895	2.629	1.504	0.597	100+	****	12.662	5.767	2.196	3.447	9.215	0.274	1.005	0.458	12.597	0.120
18	7.208	3.943	1.954	0.590	100+	****	12.961	5.753	2.253	3.604	9.357	0.271	0.974	0.432	13.313	0.165
19	8.124	5.811	2.545	0.581	100+	****	13.877	5.753	2.412	4.062	9.815	0.283	0.968	0.401	14.330	0.374
20	8.043	7.541	2.877	0.575	100+	****	13.795	5.753	2.398	4.021	9.774	0.269	0.923	0.385	14.943	0.301
21	7.939	10.066	3.183	0.570	100+	****	13.692	5.753	2.380	3.970	9.722	0.255	0.881	0.370	15.538	0.221
22	8.652	11.501	3.411	0.566	100+	****	14.412	5.760	2.502	4.326	10.086	0.270	0.901	0.360	15.999	0.409
23	7.700	14.545	3.388	0.567	100+	****	13.453	5.753	2.338	3.850	9.603	0.241	0.843	0.361	15.951	0.114
24	8.461	18.004	3.791	0.560	100+	****	14.214	5.753	2.471	4.231	9.983	0.252	0.846	0.342	16.806	0.287
25	7.740	23.193	3.934	0.558	100+	****	13.500	5.760	2.344	3.870	9.630	0.226	0.788	0.336	17.122	0.033
26	7.952	24.801	4.026	0.556	100+	****	13.705	5.753	2.382	3.976	9.729	0.229	0.791	0.332	17.330	0.085
27	6.613	33.362	4.105	0.555	100+	****	12.373	5.760	2.148	3.306	9.066	0.189	0.707	0.329	17.510	-0.352

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-26-160-1(1)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.973 IN GS: 2.72 WATER CONTENT: 26.4 %
DIAMETER: 2.877 IN DRY DENSITY: 95.2 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.783 SATURATION: 92 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.544 BY AN ISOTROPIC STRESS OF 11.54 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.544 BY AN ISOTROPIC STRESS OF 11.54 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.694 IN DIAMETER: 2.614 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 19.19 TSF

SOLUTE SUCTION: 24.1 TSF

POST-TEST WATER CONTENT: 18.3 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.544	100+	****	11.542	11.542	1.000	0.	11.542	0.	0.603	0.603	19.152	-3.633
11	2.806	0.193	0.231	0.541	100+	****	14.348	11.542	1.243	1.403	12.945	0.071	0.727	0.585	19.726	-2.794
12	5.689	0.492	0.488	0.537	100+	****	17.231	11.542	1.493	2.845	14.386	0.140	0.845	0.566	20.391	-1.938
13	8.555	0.931	0.817	0.532	100+	****	20.103	11.549	1.741	4.277	15.826	0.201	0.945	0.543	21.283	-1.106
14	10.948	1.493	1.168	0.526	100+	****	22.490	11.542	1.949	5.474	17.016	0.246	1.009	0.518	22.286	-0.429
15	13.262	2.072	1.526	0.521	100+	****	24.811	11.549	2.148	6.631	18.180	0.284	1.062	0.494	23.372	0.213
16	12.798	2.915	1.880	0.515	100+	****	24.347	11.549	2.108	6.399	17.948	0.261	0.994	0.471	24.506	-0.022
17	14.128	3.969	2.329	0.508	100+	****	25.677	11.549	2.223	7.064	18.613	0.271	0.986	0.443	26.047	0.277
18	14.507	4.900	2.664	0.503	100+	****	26.048	11.542	2.257	7.253	18.795	0.266	0.955	0.423	27.274	0.302
19	14.524	6.235	3.024	0.498	100+	****	26.066	11.542	2.258	7.262	18.804	0.253	0.909	0.403	28.669	0.198
20	14.739	7.710	3.344	0.493	100+	****	26.281	11.542	2.277	7.376	18.911	0.246	0.876	0.385	29.987	0.163
21	14.608	9.730	3.631	0.488	100+	****	26.150	11.542	2.266	7.304	18.846	0.234	0.837	0.370	31.230	0.024
22	14.655	12.329	3.912	0.484	100+	****	26.204	11.549	2.269	7.327	18.876	0.225	0.806	0.355	32.509	-0.062
23	14.076	16.491	4.167	0.480	100+	****	25.618	11.542	2.220	7.038	18.580	0.209	0.759	0.342	33.730	-0.339
24	14.097	19.793	4.365	0.477	100+	****	25.653	11.556	2.220	7.049	18.605	0.203	0.739	0.333	34.711	-0.412
25	13.064	25.044	4.572	0.474	100+	****	24.598	11.534	2.133	6.532	18.066	0.183	0.687	0.322	35.780	-0.817
26	13.133	28.275	4.765	0.471	100+	****	24.675	11.542	2.138	6.567	18.108	0.178	0.670	0.314	36.806	-0.876

PROJECT: SOIL SUCTION

SPECIMEN NO: TXS-25-DR-26-160-1(2)

AS COMPACTED SPECIMEN CHARACTERISTICS:
HEIGHT: 5.992 IN GS: 2.72 WATER CONTENT: 26.6 %
DIAMETER: 2.873 IN DRY DENSITY: 95.0 PCF

APPLIED STRESS HISTORY:
INITIAL SPECIMEN CONDITIONS:
VOID RATIO: 0.787 SATURATION: 92 % SUCTION: **** TSF
COMPRESSED TO A VOID RATIO OF 0.551 BY AN ISOTROPIC STRESS OF 11.52 TSF
SUCTION: **** TSF SATURATION: 100+%
REBOUNDED TO A VOID RATIO OF 0.551 BY AN ISOTROPIC STRESS OF 11.52 TSF
SUCTION: **** TSF SATURATION: 100+%

PRE-SHEAR CONDITIONS:
HEIGHT: 5.692 IN DIAMETER: 2.617 IN
EQUIVALENT CONSOLIDATION STRESS, P_e: 18.12 TSF

SOLUTE SUCTION: 23.9 TSF

POST-TEST WATER CONTENT: 18.5 %

TEST RESULTS:

LINE NO	DEV STRESS TSF	AXIAL STRAIN %	VOLUME STRAIN %	VOID RATIO	SAT %	SUCTION TSF	STRESS σ_1 TSF	STRESS σ_3 TSF	SRATIO σ_1/σ_3	SSTRESS "q" TSF	NSTRESS "p" TSF	NORM q/P_e	NORM σ_1/P_e	NORM σ_3/P_e	EQUIV P_e TSF	QPSY q_ψ TSF
10	0.	0.000	0.	0.551	100+	****	11.520	11.520	1.000	0.	11.520	0.	0.633	0.633	18.187	-3.553
11	1.203	0.070	0.005	0.550	100+	****	12.723	11.520	1.104	0.602	12.121	0.033	0.699	0.633	18.199	-3.175
12	1.095	0.123	-0.002	0.551	100+	****	12.615	11.520	1.095	0.547	12.067	0.030	0.694	0.634	18.183	-3.208
13	2.936	0.193	0.053	0.550	100+	****	14.463	11.527	1.255	1.468	12.995	0.080	0.790	0.630	18.309	-2.639
14	3.948	0.281	0.109	0.549	100+	****	15.482	11.534	1.342	1.974	13.508	0.107	0.840	0.626	18.440	-2.332
15	4.562	0.369	0.208	0.547	100+	****	16.090	11.527	1.396	2.281	13.808	0.122	0.862	0.617	18.675	-2.156
16	5.655	0.457	0.286	0.546	100+	****	17.182	11.527	1.491	2.828	14.355	0.150	0.911	0.611	18.861	-1.826
17	6.536	0.562	0.393	0.544	100+	****	18.063	11.527	1.567	3.268	14.795	0.171	0.945	0.603	19.120	-1.569
18	7.701	0.720	0.503	0.543	100+	****	19.228	11.527	1.668	3.851	15.378	0.199	0.992	0.594	19.393	-1.223
19	8.732	0.896	0.631	0.541	100+	****	20.266	11.534	1.757	4.366	15.900	0.221	1.028	0.585	19.715	-0.925
20	9.919	1.124	0.813	0.538	100+	****	21.454	11.534	1.860	4.960	16.494	0.246	1.063	0.571	20.183	-0.588
21	11.706	1.792	1.114	0.533	100+	****	23.240	11.534	2.015	5.853	17.387	0.279	1.107	0.549	20.992	-0.088
22	12.634	2.530	1.427	0.528	100+	****	24.161	11.527	2.096	6.317	17.844	0.289	1.105	0.527	21.872	0.137
23	13.044	3.637	1.800	0.523	100+	****	24.579	11.534	2.131	6.522	18.057	0.284	1.069	0.502	22.982	0.178
24	14.141	4.656	2.134	0.517	100+	****	25.682	11.542	2.225	7.070	18.612	0.294	1.069	0.480	24.033	0.440
25	15.196	7.519	2.813	0.507	100+	****	26.716	11.520	2.319	7.598	19.118	0.288	1.013	0.437	26.362	0.594
26	14.301	10.647	3.117	0.502	100+	****	25.828	11.527	2.241	7.150	18.677	0.260	0.939	0.419	27.495	0.222
27	15.063	16.058	3.603	0.495	100+	****	26.583	11.520	2.308	7.531	19.051	0.256	0.903	0.391	29.429	0.312
28	14.128	20.942	3.809	0.491	100+	****	25.655	11.527	2.226	7.064	18.591	0.233	0.847	0.380	30.297	-0.052
29	14.619	22.997	3.973	0.489	100+	****	26.138	11.520	2.269	7.309	18.829	0.236	0.843	0.371	31.013	0.048
30	12.527	30.358	4.128	0.487	100+	****	24.054	11.527	2.087	6.264	17.791	0.198	0.759	0.364	31.707	-0.666